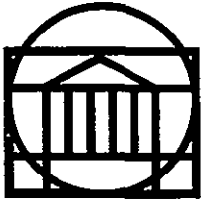


RESEARCH LABORATORIES FOR THE ENGINEERING SCIENCE



SCHOOL OF ENGINEERING AND  
APPLIED SCIENCE

University of Virginia

Charlottesville, Virginia 22901

VALIDATION OF THE PASSENGER RIDE QUALITY APPARATUS (PRQA)  
FOR SIMULATION OF AIRCRAFT MOTIONS FOR RIDE-QUALITY RESEARCH

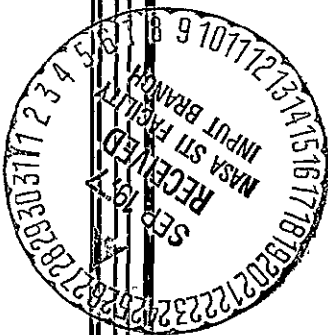
Technical Report  
NASA Grant No. NGR 47-005-181

Submitted to:

NASA Scientific and Technical Information Facility  
P. O. Box 8757  
Baltimore/Washington International Airport  
Maryland 21240

Submitted by:

William B. Bigler II



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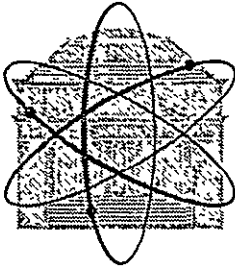
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RESEARCH LABORATORIES FOR THE ENGINEERING SCIENCES

THORNTON HALL • UNIVERSITY OF VIRGINIA • CHARLOTTESVILLE 22901

September 22, 1977

Mr. D. W. Conner  
NASA/Langley Research Center  
Mail Stop 249A  
Hampton, Virginia 23665

Subject: Technical Report  
Grant No. NGR 47-005-181

Dear Mr. Conner:

We are enclosing three (3) copies of our Technical Report prepared under NASA Grant No. NGR 47005181 entitled "Validation of the Passenger Ride Quality Apparatus (PRQA) for Simulation of Aircraft Motions for Ride-Quality Research," submitted by Mr. William B. Bigler, II of the Department of Engineering Science and Systems.

If we can be of assistance in any way, please do not hesitate to contact us.

Very truly yours,

(Mrs.) S. B. Sullivan  
Publications Supervisor

SBS:pm

Enclosures: (3) RLES Report No. UVA/528060/ESS77/108

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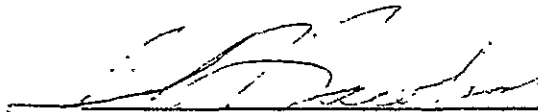
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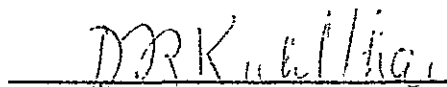
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Report No. UVA/528060/ESS77/108

April 1977

Copy No. 4

## SUMMARY .

Advantages of using a ground-based simulator to substitute for a flight vehicle include decreased costs, more control over stimuli, elimination of adverse weather factors, and less turnaround time between tests. In order to validate ground-based simulators for studying aircraft passenger ride quality, the University of Virginia (UVA) conducted a research program on the NASA Passenger Ride Quality Apparatus (PRQA), a ground-based simulator located at the Langley Research Center. The test stimuli, used in the program, were taken from flight test data generated on The Total In-Flight Simulator (TIFS).

Four tests were made on PRQA with varying stimuli: 1) motions only; 2) motions and noise; 3) motions, noise, and visual; and 4) motions and visual. Subjects were volunteers from UVA and NASA.

Direct comparison of the means of the comfort responses was hampered in that the ground-based simulator could not achieve the RMS magnitudes in vertical motions that the in-flight simulator could. Regression equations for each of four PRQA tests and TIFS were obtained and subsequent t-testing of the slopes indicated that ground-based simulator tests, with both motion and noise stimuli present, produced comfort change rates similar to the flight data. The motion/visual combination did not produce similarity, but, when blended with noise, it did not detract from the similarity caused by the motion/noise combination. Further comparison of the motion power spectral densities indicated two areas of dissimilarity but one is not required for effective simulation and the other is associated with only "possible" adverse passenger reactions.

Recommendations include that PRQA be used in the ride-quality program for aircraft and that it be validated for other transportation modes.

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## LIST OF SYMBOLS

|                 |                                                                       |
|-----------------|-----------------------------------------------------------------------|
| $A$             | = One group of subjects                                               |
| $a$             | = Constant of comfort equation                                        |
| $a_z$           | = Vertical acceleration                                               |
| $B$             | = Other group of subjects                                             |
| $b_{p_i}$       | = Slope of comfort equation for PRQA test $i$ ; $i = 1,2,3,4$         |
| $b_T$           | = Slope of comfort equation for TIFS                                  |
| $\bar{C}$       | = Mean of comfort ratings                                             |
| $\bar{C}_{p_i}$ | = Mean of comfort ratings for PRQA test $i$ ; $i = 1,2,3,4$           |
| $\bar{C}_T$     | = Mean of comfort ratings for TIFS test                               |
| $D$             | = t-test comparison results indicate difference                       |
| $d$             | = Abscissa parameter for operating curve charts                       |
| $g$             | = Force of gravity                                                    |
| $H_0$           | = Null hypothesis                                                     |
| $H_1$           | = Alternative hypothesis                                              |
| $H_z$           | = Hertz, measure of frequency                                         |
| $K$             | = Independent variable of the normal function                         |
| $K_{cr}$        | = Critical values of $K$ corresponding to a particular $\alpha$ value |
| $n$             | = Sample size                                                         |
| PSD             | = Power Spectral Density                                              |
| $r$             | = Coefficient of correlation                                          |
| $r^2$           | = Coefficient of determination                                        |
| RMS             | = Root-Mean-Square                                                    |

## INTRODUCTION

Advantages of using a ground-based simulator to substitute for a flight vehicle include decreased costs, improved test condition control, elimination of adverse weather condition factors, and less turnaround time between tests, and more control over the test environment. The major disadvantage is the possibility that it does not adequately represent the "true" environment encountered in flight.

In order to validate ground-based simulators for studying aircraft passenger ride quality, the University of Virginia (UVA) and the Langley Research Center of the National Aeronautics and Space Administration (NASA/Langley) co-sponsored a research program on the Passenger Ride Quality Apparatus (PRQA), a ground-based simulator located at Langley (11). The test stimuli, used in the program, were taken from previous flight tests on The Total In-flight Simulator (TIFS) (6, Tables 2 and 3). The analysis logic utilized a series of t-tests to compare the comfort response means,  $\bar{C}$  (5, page 4).

The testing took place on 26 September 1975 with a total of 13 subjects being used for the four tests on PRQA. Motion data were collected on magnetic tape and analyzed by the Data Transcription facility at NASA/Langley. Comfort data were recorded on individual subject response sheets and analyzed at UVA with the HP-2000A and the CDC-6400 computers. All comparisons used TIFS data as a base-line for analysis.

## TEST METHODOLOGY

The PRQA program utilized a drive tape, prepared from Flight 333 of the TIFS project, which provided vertical and transverse input motions to the simulator. Test subjects were asked to evaluate their comfort upon being subjected to the motions or to the motions in combination with audio and/or visual stimuli. Approximately every two minutes of a test run, the subjects were asked to record their comfort evaluation using a 7-point rating scale (3). Figure 1 shows the rating sheet and scale used. Twelve subjects (6/run) were exposed to each test in the series (6, page 2). The test series consisted of four tests with stimuli as follows: 1) motions only; 2) motions and noise; 3) motions, noise, and visual; and 4) motions and visual. Figure 2 shows the test schedule with subject grouping.

PRQA's characteristics, both motion environment and cabin environment, are documented in the validation study report (11). The simulator drive tape was prepared by copying the output tape from the first ten segments of Flight 333 of the TIFS project (9, page 52). The tape was inspected for motion discontinuities and motions which exceeded PRQA's limits. During playback through the simulator, the vertical input accelerations had to be reduced by 40% to prevent an overload of the simulator's automatic safety system.

Test subjects, from UVA and NASA/Langley, were utilized by dividing them into two groups. To facilitate identification of possible factors, causing variation among the comfort responses, each subject provided the following information:

Figure 1 PRQA SIMULATOR RESPONSE SHEET

Rating Scale

Test Flight No. \_\_\_\_\_

- 1 Very Comfortable
- 2 Comfortable
- 3 Slightly Comfortable
- 4 Neutral
- 5 Slightly Uncomfortable
- 6 Uncomfortable
- 7 Very Uncomfortable

| Segment No. | Comfort Rating | Comment |
|-------------|----------------|---------|
| 1           |                |         |
| 2           |                |         |
| 3           |                |         |
| 4           |                |         |
| 5           |                |         |
| 6           |                |         |
| 7           |                |         |
| 8           |                |         |
| 9           |                |         |
| 10          |                |         |

| <u>Time</u> | <u>Activity/Group</u> | <u>Stimuli</u>            |
|-------------|-----------------------|---------------------------|
| 0900        | Pre-Briefing          |                           |
| 0930        | Test 1A               | Motions                   |
| 0950        | Change Subjects       |                           |
| 1000        | Test 1B               | Motions                   |
| 1020        | Change Subjects       |                           |
| 1030        | Test 2A               | Motions and Noise         |
| 1050        | Change Subjects       |                           |
| 1100        | Test 2B               | Motions and Noise         |
| 1120        | Post-Briefing         |                           |
| 1130        | Lunch                 |                           |
| 1300        | Pre-Briefing          |                           |
| 1310        | Test 3A               | Motions, Noise and Visual |
| 1330        | Change Subjects       |                           |
| 1340        | Test 3B               | Motions, Noise and Visual |
| 1400        | Change Subjects       |                           |
| 1410        | Test 4A               | Motions and Visual        |
| 1430        | Change Subjects       |                           |
| 1440        | Test 4B               | Motions and Visual        |
| 1500        | Post-Briefing         |                           |
| 1510        | Dismissal             |                           |

The numeral in the test designation refers to the test number and the letter refers to the subject group.

Figure 2. PRQA TEST SCHEDULE

Age

Number of flights

Types of aircraft

Number of simulator flights

Attitude towards flying

In addition to the above, each subject was asked to provide a description of his or her interpretation of the 7-point comfort rating scale. This interpretation was supplied after the subject had experienced at least one test run on PRQA. Prior to the first run of the day, the subjects were briefed with regard to the simulator's safety aspects and the type of testing to be accomplished. This briefing was in accordance with the NASA approved procedures concerning human subject testing.

Two additional stimuli, audio and visual, were used in combination with the motion stimulus. The audio stimulus was interior cabin noise recorded on TIFS flights. The noise was introduced into the simulator cabin via two speakers located on the front and rear walls as shown in Figure 3. The visual cue, a film made by the University Public Relations Department of UVA during a flight in a Grumman American Traveler AA-5 (a small single-engine airplane), was shown to the subjects through the cabin windows as shown in Figure 3.

Appendix A shows a summary of the seating assignments and the tests to which each subject was exposed during the PRQA research program.

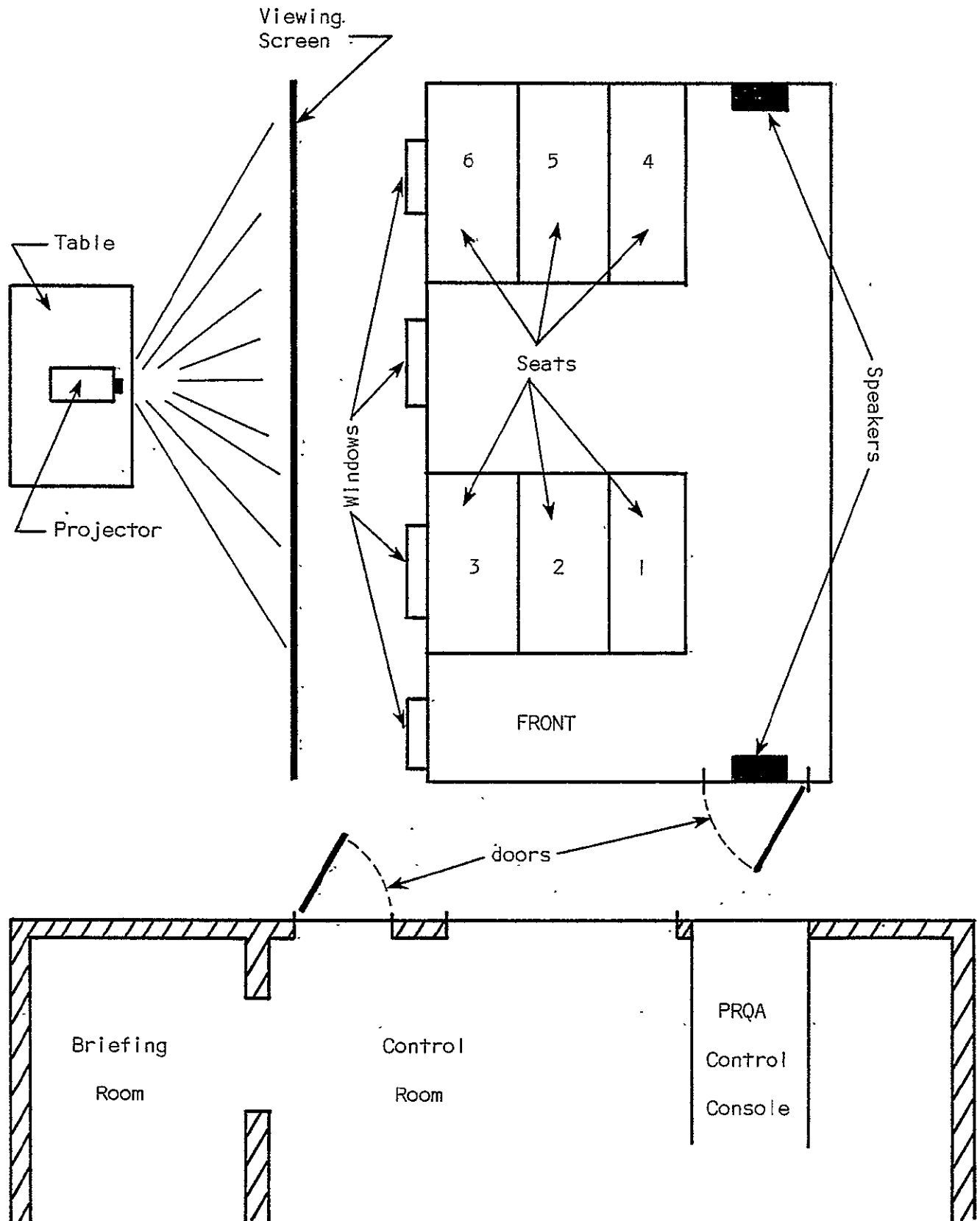


Figure 3 PRQA Laboratory Arrangement

## TEST RESULTS

Appendix B shows the results of the TIFS Flight 333, the base-line for this validation effort; the PRQA Program vertical motion RMS values; and the PRQA subjective comfort response means. Since the transverse motions of Flight 333 were approximately constant, the PRQA transverse motions were checked to insure they were also constant with approximately the same RMS values; these motions were satisfactory.

Numerical and graphical comparisons between the vertical motion RMS values of the four PRQA tests and TIFS are shown in Figures 4 and 5. Although the motion direction changes were identical, the magnitudes of the RMS values were very different from both the TIFS values and the expected values (the 40% reduction due to PRQA motion input limitations). For that reason the means of the comfort responses,  $\bar{C}$ , had to be compared between the following combinations of segments:

| <u>TIFS Segment</u> | <u>PRQA Segment</u> |
|---------------------|---------------------|
| 1                   | 5, 10               |
| 2                   | 6                   |
| 8                   | 4, 9                |

Figure 6 compares the matched pairs of segments. t-test comparisons of the comfort means for differences of less than 0.5 (5, page 3), did not indicate any PRQA test as being similar to the TIFS base-line. Subsequent graphical comparisons, which are explained later, revealed a constant bias of approximately 2.0 between the PRQA and TIFS results. t-test comparisons, for mean differences of less than 2.0, yielded results, shown in Figure 7, which indicated that most segments were similar. Since none of the original



| Test<br>Segment | 1     | 2     | 3     | 4     | TIFS  | Expected<br>Value * |
|-----------------|-------|-------|-------|-------|-------|---------------------|
| 1               | .0164 | .0161 | .0163 | .0163 | .0148 | .0152               |
| 2               | .0196 | .0195 | .0195 | .0178 | .0449 | .0270               |
| 3               | .0287 | .0285 | .0293 | .0274 | .0810 | .0486               |
| 4               | .0316 | .0317 | .0331 | .0310 | .1015 | .0609               |
| 5               | .0251 | .0250 | .0258 | .0239 | .0621 | .0373               |
| 6               | .0430 | .0430 | .0425 | .0399 | .1468 | .0881               |
| 7               | .0197 | .0199 | .0202 | .0194 | .0549 | .0329               |
| 8               | .0156 | .0156 | .0153 | .0148 | .0320 | .0192               |
| 9               | .0328 | .0331 | .0314 | .0304 | .1095 | .0657               |
| 10              | .0263 | .0264 | .0254 | .0250 | .0896 | .0538               |

All values are RMS values for vertical acceleration

\* Expected Value = .6 of TIFS value (limitation on motion input)

Figure 4 Numerical Comparison of Vertical Motions

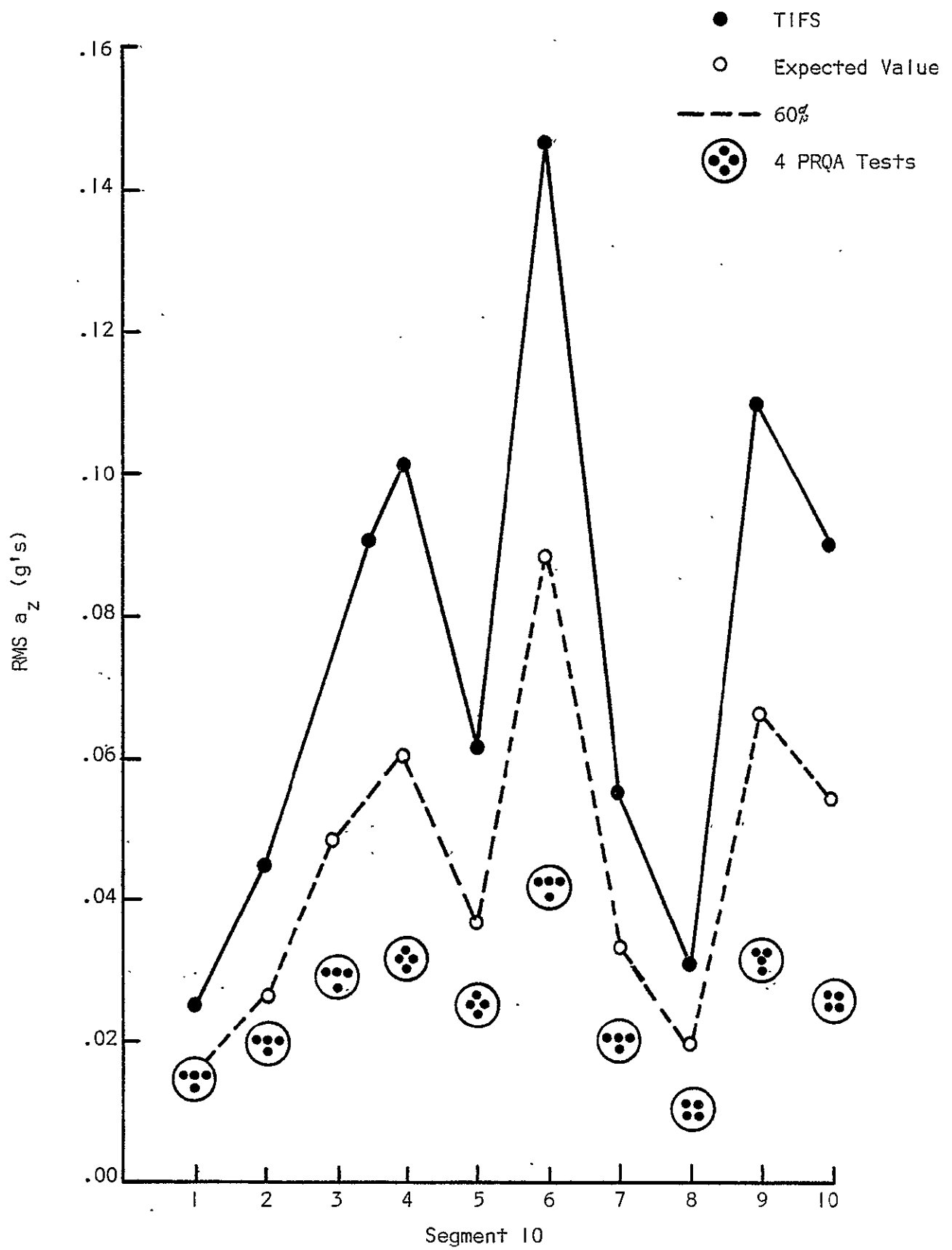


Figure 5 Graphical Comparison of Vertical Motions

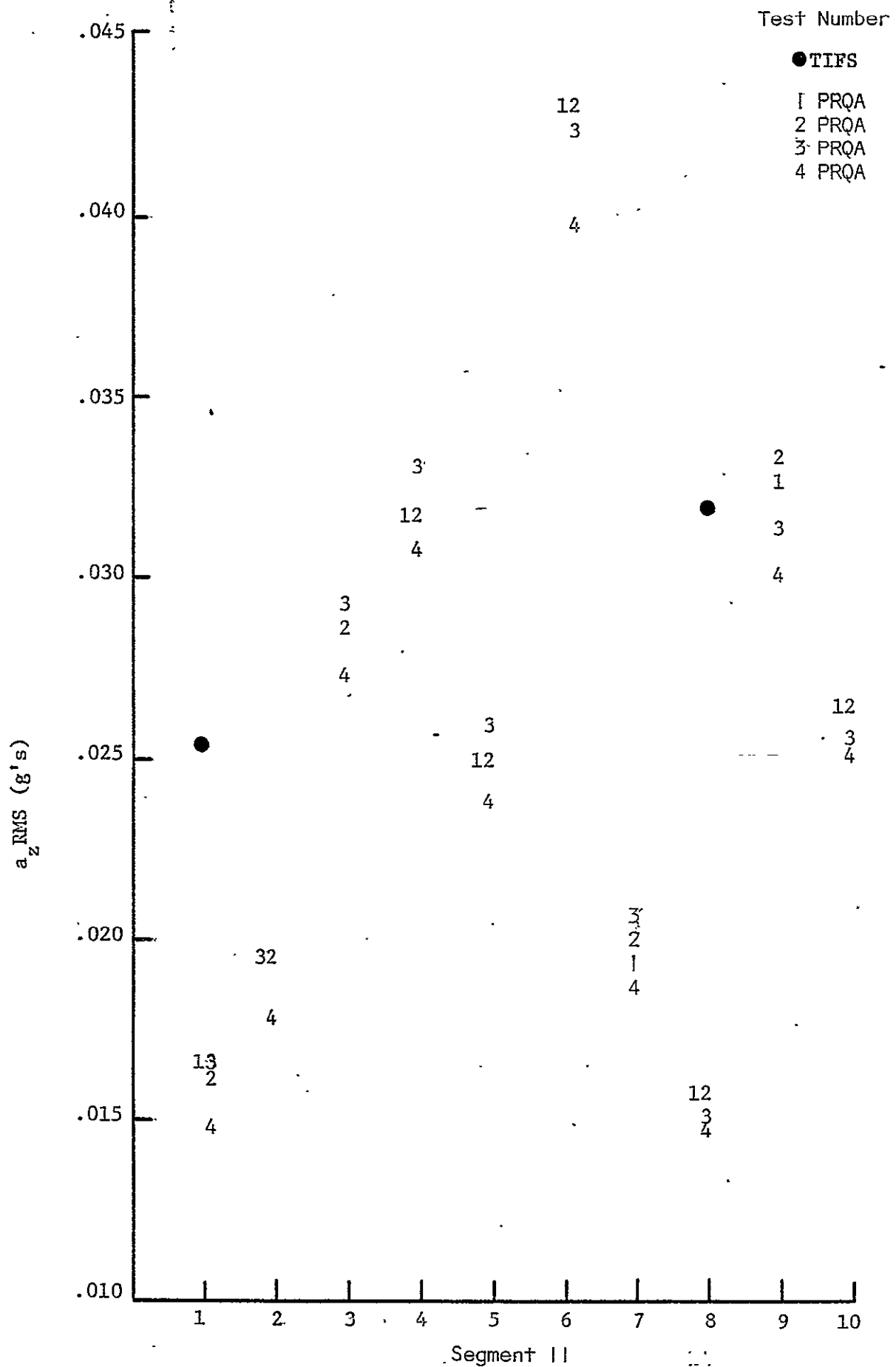


Figure 6 Graphical Comparison of Selected Segment Pairs

| Segments | TIFS to<br>Test 1 | TIFS to<br>Test 2 | TIFS to<br>Test 3 | TIFS to<br>Test 4 |
|----------|-------------------|-------------------|-------------------|-------------------|
| 1 - 5    | S                 | D                 | S                 | S                 |
| 1 - 10   | S                 | S                 | S                 | S                 |
| 2 - 6    | S                 | S                 | S                 | S                 |
| 8 - 4    | S                 | S                 | S                 | S                 |
| 8 - 9    | S                 | S                 | S                 | S                 |

Hypotheses Tested:

$$H_0: |\bar{C}_{p_i} - \bar{C}_T| \leq 2.0$$

$$H_1: |\bar{C}_{p_i} - \bar{C}_T| > 2.0$$

S = means are similar

D = means are different

FIGURE 7 T-Test Results for  $\bar{C}$  Comparisons

comparisons showed any PRQA test similar to the TIFS results, regression equations were generated for each PRQA test data set and the TIFS data set to facilitate statistically testing the similarity of the slopes, i.e. the comfort change rates.

If the slopes of the regression lines are similar, then it can be assumed that PRQA and TIFS cause the same subjective changes in human subjects. This conclusion would still allow the PRQA to be validated, provided that the mathematical relationship between the TIFS regression equation and the PRQA regression equations could be established.

Utilization of the HP-2000A computer curve fitting program provided the slopes as shown in Figure 8, necessary for t-test comparisons.

The hypothesis for testing the similarity of the slopes was formulated as:

$$|b_{P_i} - b_T| \geq \Delta$$

where

$b_{P_i}$  = slope for the PRQA  $i^{\text{th}}$  test;  $i = 1, 2, 3, 4$

$b_T$  = slope for TIFS

$\Delta$  = difference of slopes which is significant.

Appendix C provides the rationale behind the hypothesis formulation. The  $\Delta$  value was chosen to be 3% of the TIFS slope or 0.5744. Appendix C explains the selection process. The general expression for t-tests of slopes with small samples (12, page 247) is:

$$t = \frac{(b_{P_i} - b_T - \Delta)}{\frac{\sqrt{1 - r^2}}{\sqrt{n-2}}}$$

| Test   | n  | a      | b       | $S_{y x}$ | $r^2$   |
|--------|----|--------|---------|-----------|---------|
| Test 1 | 18 | 2.2714 | 49.7617 | 21.4465   | .251764 |
| Test 2 | 20 | 3.4047 | 18.5140 | 18.6095   | .052121 |
| Test 3 | 19 | 2.9294 | 15.3870 | 12.9315   | .076881 |
| Test 4 | 20 | 2.5577 | 22.5480 | 24.5443   | .044786 |
| TIFS   | 10 | 1.4147 | 19.1452 | 2.9763    | .837986 |

$n_i$  = sample size

$a_i$  = constant for regression equation

$b_i$  = slope for regression equation

$S_{y|x}$  = standard error of the estimate

$r^2$  = coefficient of determination

Figure 8 Computer Regression Results

where

$t = t$  static

$n$  = sample size

$r^2$  = coefficient of determination.

The level of significance,  $\alpha$ , was chosen to be 0.01 and Appendix C provides the detailed derivation of the  $t$  equation and  $\alpha$ . Just as the original proposal to test the comfort means produced paired sets of hypotheses (5, page 3), this comparison also requires paired sets as follows:

| <u>Set A</u>                     | <u>Set B</u>                     |
|----------------------------------|----------------------------------|
| $H_0: b_{P_i} - b_T \geq 0.5744$ | $H_0: b_{P_i} - b_T \leq 0.5744$ |
| $H_1: b_{P_i} - b_T < 0.5744$    | $H_1: b_{P_i} - b_T > 0.5744$    |

Figure 9 shows the results of the  $t$ -tests using the information from the regression analysis and comparing the above  $t$ -statistic values and  $t$ -critical values for  $\alpha = 0.01$  and  $n-2$  degrees of freedom. Thus, if motion is used in combination with a noise stimuli, PRQA can reproduce similar change rates in passenger comfort as the TIFS simulator. Additionally, if a visual stimulus is used with the motion/noise combination stimuli, the change rates in passenger comfort are similar. However, the absence of the noise stimulus caused different change rates of comfort.

The next step was to graph  $\bar{C}$  versus RMS values of the vertical motions for each test in order to identify the relationship between the two simulator's equations. Figures 10, 11, and 12 show the regression lines for PRQA tests 2, 3, and 4, respectively. These figures clearly show that the regression lines are very close to being parallel but that the PRQA

| TIFS vs | Set No. | t        | t <sub>cr</sub> | Result |
|---------|---------|----------|-----------------|--------|
| Test 1  | A       | 138.9220 | 2.552           | D      |
|         | B       | 144.2343 | -2.552          | S      |
| Test 2  | A       | -5.2537  | 2.528           | S      |
|         | B       | -.2475   | -2.528          | S      |
| Test 3  | A       | -18.5928 | 2.539           | S      |
|         | B       | -1.4466  | -2.539          | S      |
| Test 4  | A       | 12.2780  | 2.528           | D      |
|         | B       | 17.2649  | -2.528          | S      |

t<sub>cr</sub> = critical t value for  $\alpha = .01$  and n - 2 degrees of freedom.

S = b<sub>p<sub>i</sub></sub> and b<sub>T</sub> are similar

D = b<sub>p<sub>i</sub></sub> and b<sub>T</sub> are different

Figure 9 T-Test Results for Slope Comparisons



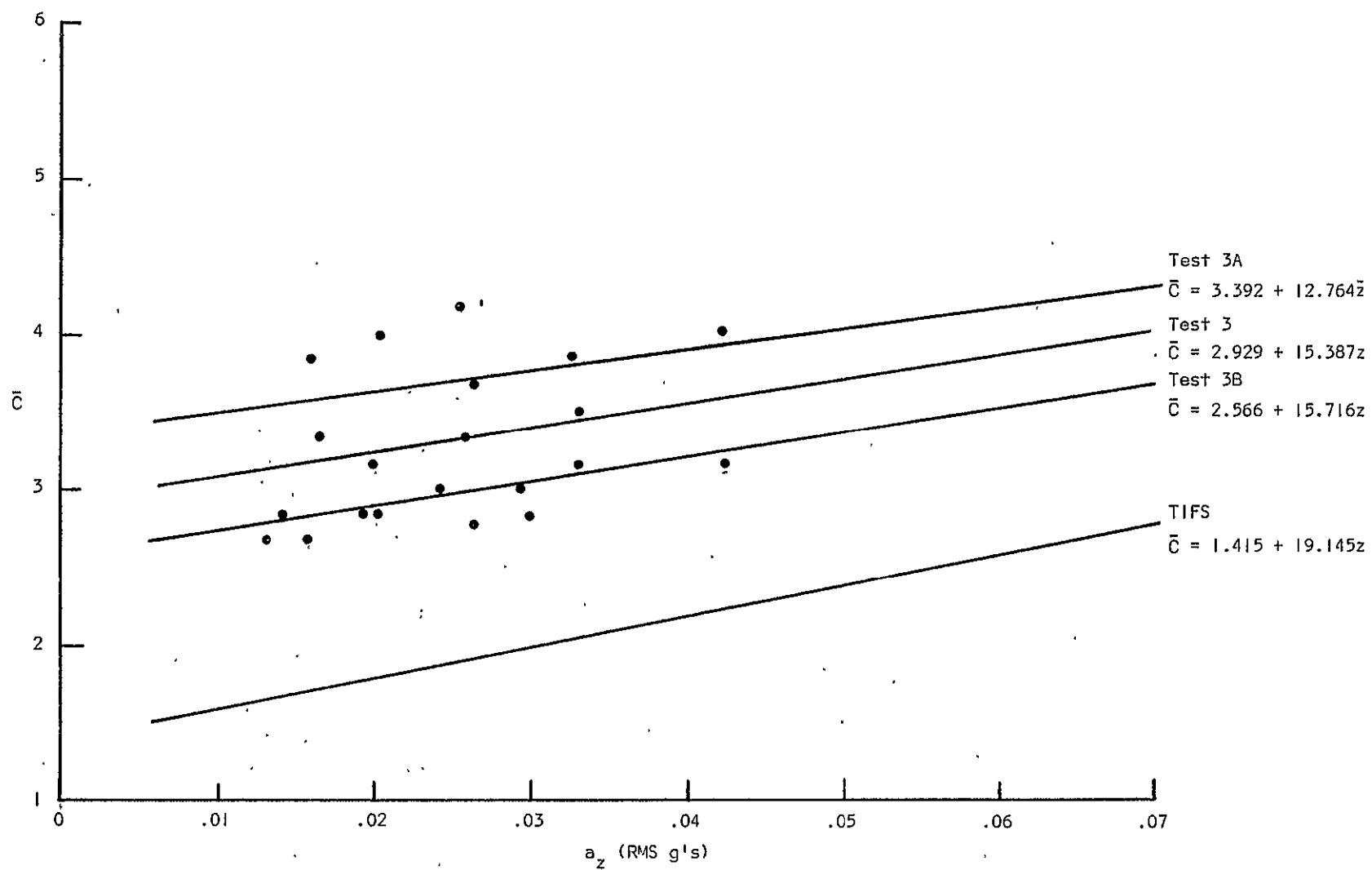


Figure 10  $\bar{C}$  vs  $a_z$  for Test 2, MOTIONS and NOISE CUES

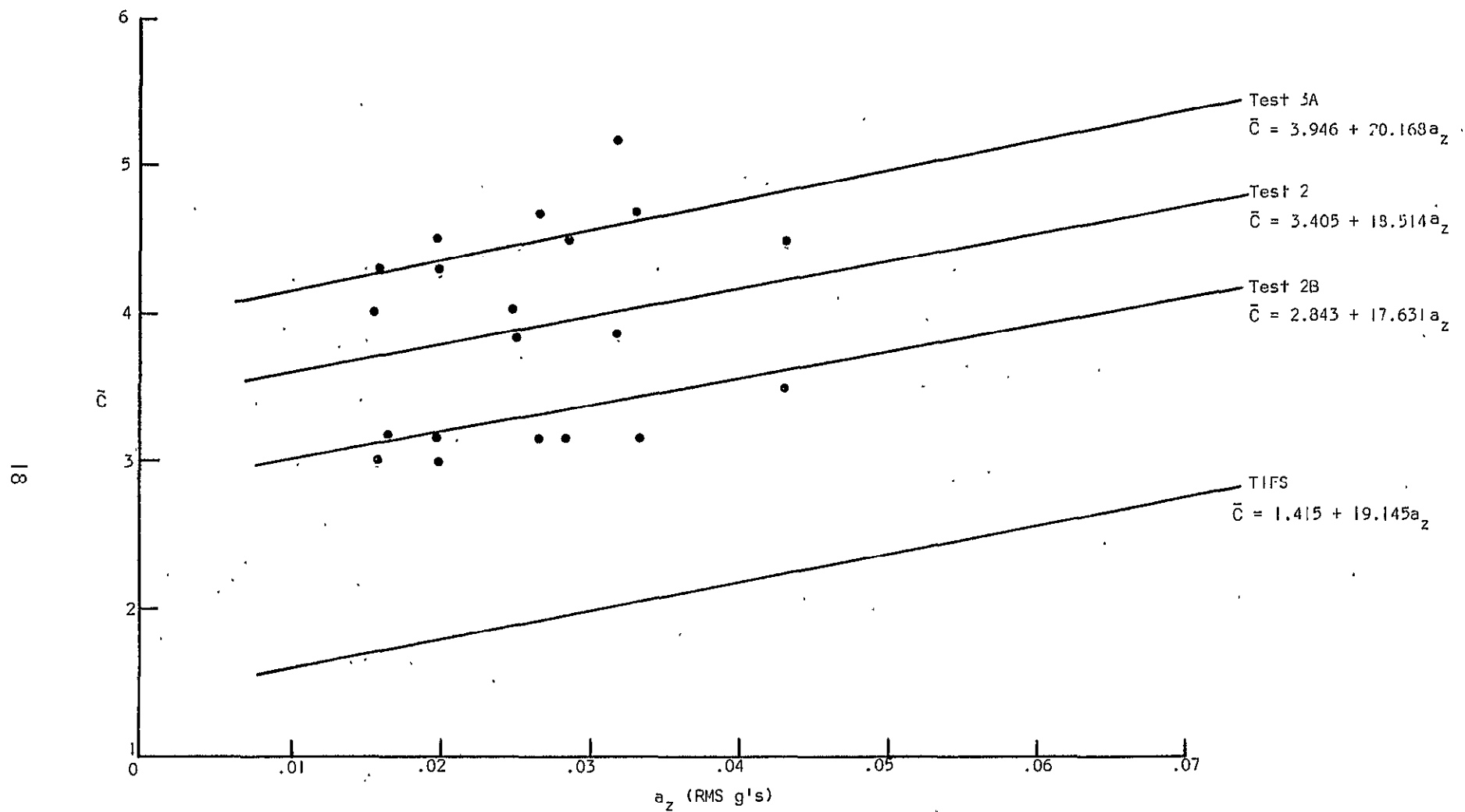


Figure 11  $\bar{C}$  vs  $a_z$  for Test 3 MOTIONS, NOISE, VISUAL CUES

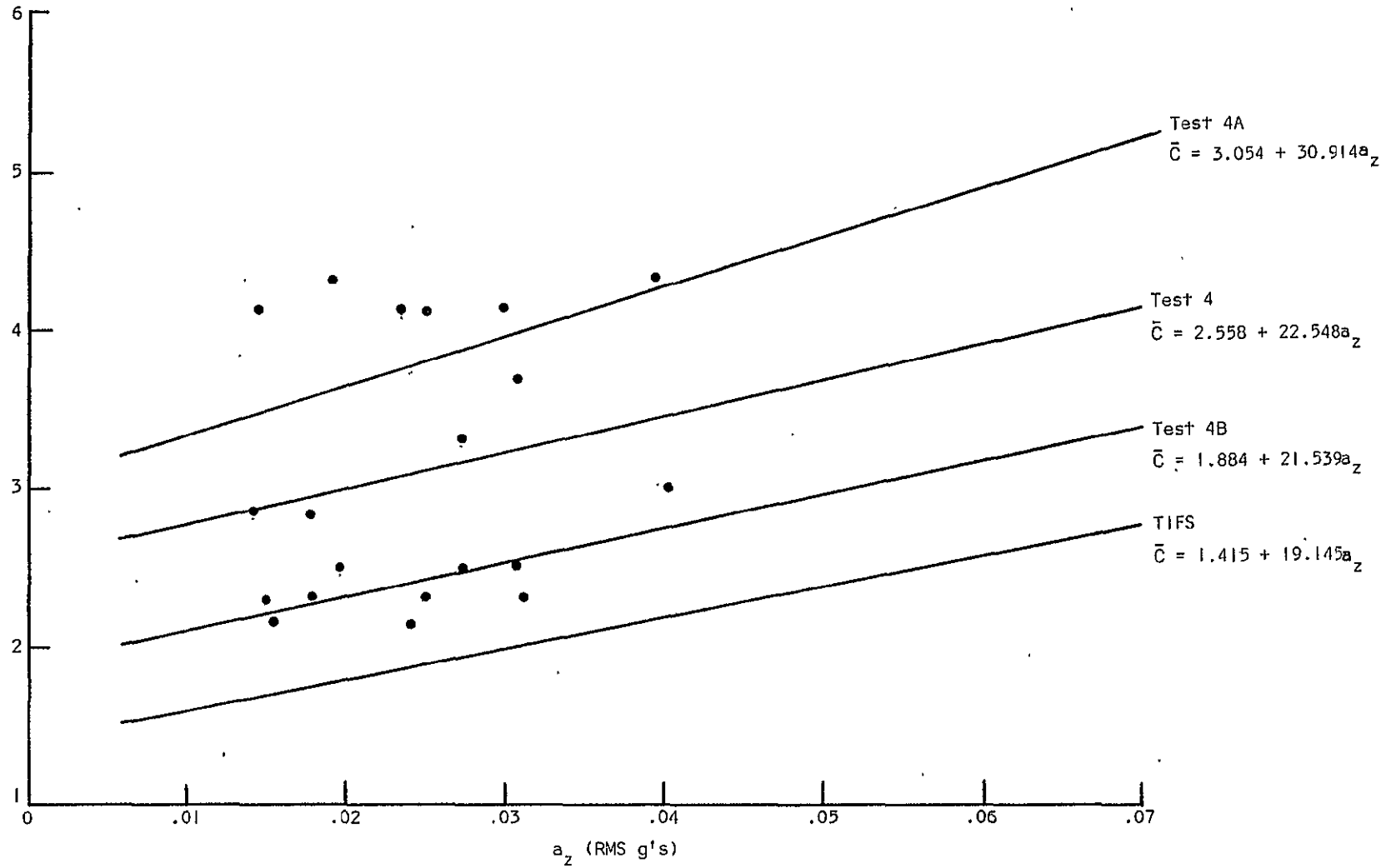


Figure 12  $\bar{C}$  vs  $a_z$  for Test 4, MOTIONS and VISUAL CUES

equations are always greater than the TIFS expression. Hence, PRQA, using motion and noise stimuli, can reproduce similar changes in passenger comfort and TIFS, but the magnitude of the average comfort,  $\bar{C}$ , will always be greater.

Two general comments about the stimuli from the subjects should be noted at this point. Some subjects indicated that the noise did not sound like TIFS and others objected to the sound because it obviously came from two point sources as opposed to originating from the structure as in TIFS. These unfavorable comments about the audio stimulus apparently did not seem to adversely affect the comfort change rates but might account for the higher  $\bar{C}$  magnitudes. Secondly, some subjects commented on the poor visual film saying that it was not representative of the kind of view a person would see on an airline. They said the film had too many bumps and was too close to the ground. Furthermore, they complained that the camera angle magnified the bumps and that the bumps were not synchronized with the PRQA motion tape. These criticisms seem to be reflected in responses as the visual cue with motions did not cause similarity between the comfort damage rates of the two simulators (comparison of PRQA test 4 and PRQA test 1 t-test results), but the visual stimulus did not appear to detract from the reality when the noise stimulus was present (comparison of PRQA test 2 and test 4 t-test results). Thus improvements in the audio stimulus might reduce the magnitude of the mean comfort response and improvements in the visual stimulus might enhance the use of this stimulus in PRQA for ride-quality testing.

Graphical representation of the test results pointed out a difference in the average comfort response of the two PRQA test groups. Preliminary examination of this variation, using the factors identified in the flight experience profiles, Appendix D, and the SPSS computer program, indicated that a significant reason for the variation was previous flight experience on TIFS. Regression analysis of age, TIFS-experience, and flight-experience

factors produced r values of:

| <u>Factor</u>     | <u>r</u> |
|-------------------|----------|
| Age               | 0.330    |
| TIFS Experience   | 0.506    |
| Flight Experience | 0.058    |
| All Above Factors | 0.560    |

Finally, the motion fidelity of the simulation was examined by comparing the power spectral densities (PSD) of the inputted motions, taken from TIFS, and the PRQA motions for the vertical motions. The PSDs, graphed in Appendix E, appear to be similar except for two regions of the frequency spectrum: less than 2.0 Hz, and 10-12 Hz. Schoultz indicated the PRQA's reproducibility was poor below 1.0 Hz (11); the PSDs indicate that this limitation starts at 2.0 Hz, but low frequency replication is not necessary for simulation (7, page 18). Poor replication in the 10-12 Hz band was evaluated using the Bioastronautics Data Book (10). The data book concludes that for seated subjects, the important frequencies are 4-6 Hz, whole body resonance, and around 10 Hz, maximum hip amplification (10, page 332). Linder describes human biological responses in the 10-15 Hz range, for the vertical RMS values of the PRQA research, as causing "possible" excretory urges and throat sensations (8, page 945). So the areas of poor duplication were either already known or only cause possible sensations in passengers and the important frequencies of whole body resonance are adequately duplicated. Hence, motions, which cause adverse passenger reactions, will not be lost in the utilization of PRQA for ride-quality research.

Comparison of these results in relation to the field work, which UVA has undertaken in the ride-quality research program (3), indicates that both constants and slopes for PRQA test 2 and 3, TIFS, and the UVA comfort model

| Model                                 | a   | b    |
|---------------------------------------|-----|------|
| Test 2                                | 3.4 | 18.5 |
| Test 3                                | 2.9 | 15.4 |
| TIFS                                  | 1.4 | 19.1 |
| UVA                                   | 2.1 | 18.9 |
| General model is $\bar{C} = a + ba_z$ |     |      |

Figure 13 Comparison of Comfort Models

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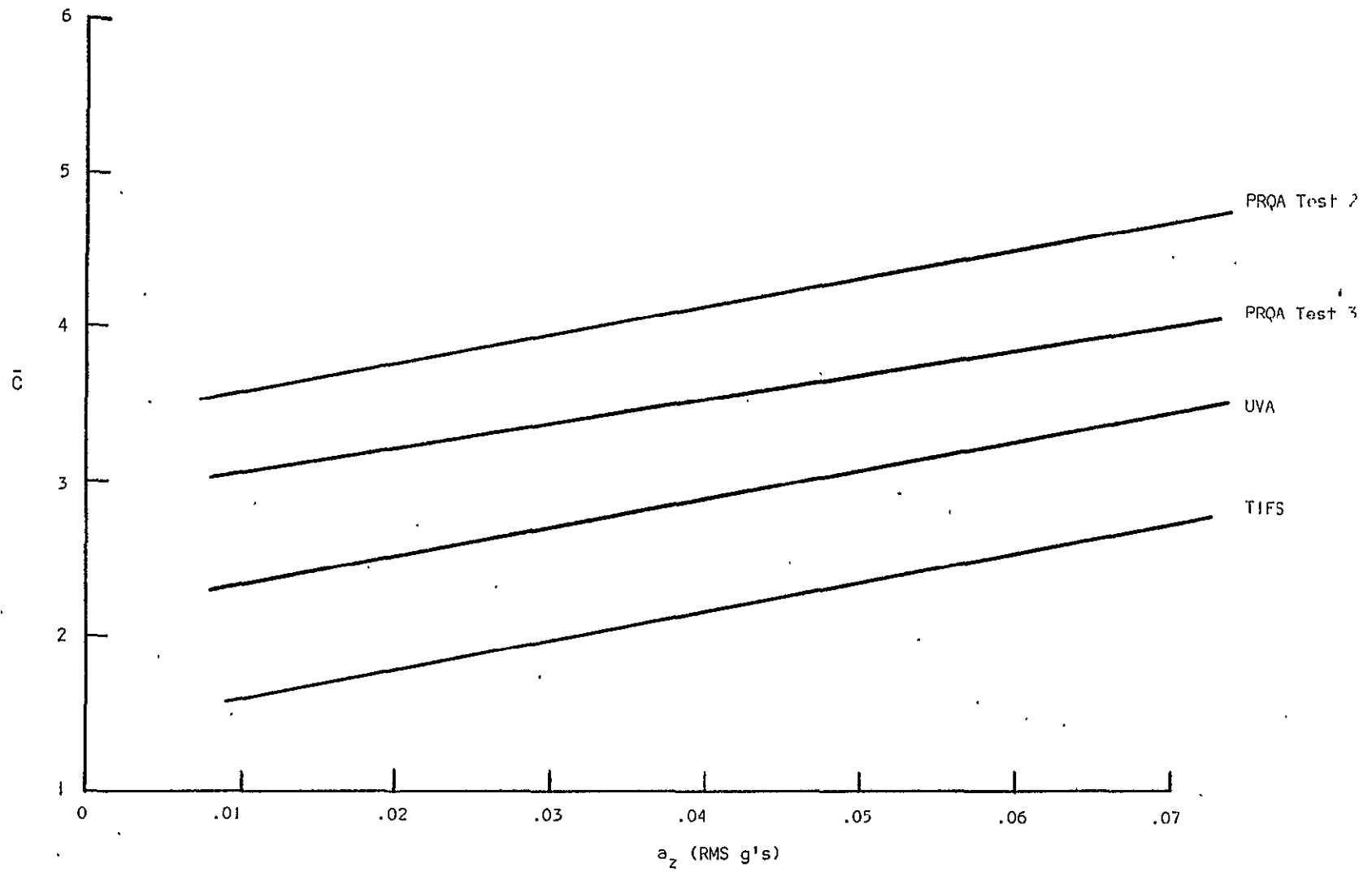


Figure 14 Graphical Comparison of Comfort Models

## CONCLUSIONS

Based upon the above results, the following conclusions have been drawn:

1. The PRQA simulator can reproduce the motions of actual aircraft in all important frequency regions.
2. PRQA can be a substitute for in-flight testing of comfort if audio stimuli is used in combination with the motion stimuli.
3. PRQA produces similar change rates in passenger comfort responses, but the magnitude of the response is always greater.
4. Previous flight experience on TIFS has been identified as making a major contribution to the difference between the two PRQA test groups' comfort responses.



## RECOMMENDATIONS

1. PRQA be used as a substitute test vehicle for ride-quality research for aircraft.
2. More speakers be added to the PRQA cabin to enable the audio stimulus to be more evenly distributed.
3. Visual cues, which more accurately represent the view that passengers will have from the simulated flight vehicle, be obtained or made.
4. PRQA be validated for ride-quality work in other transportation modes.
5. Future testing, involving more than one test group, be carefully analyzed with respect to group differences.

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# APPENDIX A

## PRQA SEATING AND TESTING ASSIGNMENT BY SUBJECT

| <u>Subject<br/>Code</u> | <u>Total<br/>Tests</u> | <u>Test Run</u> |           |           |           |           |           |           |           |
|-------------------------|------------------------|-----------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
|                         |                        | <u>1A</u>       | <u>1B</u> | <u>2A</u> | <u>2B</u> | <u>3A</u> | <u>3B</u> | <u>4A</u> | <u>4B</u> |
| 01                      | 4                      | 4               |           | 1         |           | 3         |           | 4         |           |
| 02                      | 3                      | 6               |           |           |           | 4         |           | 2         |           |
| 03                      | 4                      | 5               |           | 6         |           | 5         |           | 1         |           |
| 04                      | 4                      | 1               |           | 5         |           | 2         |           | 6         |           |
| 05                      | 4                      | 2               |           | 2         |           | 6         |           | 5         |           |
| 06                      | 3                      |                 | 4         |           | 5         |           | 1         |           |           |
| 07                      | 4                      | 3               |           | 3         |           | 1         |           | 3         |           |
| 08                      | 2                      |                 |           | 4         |           |           |           |           | 1         |
| 09                      | 4                      |                 | 6         |           | 1         |           | 3         |           | 3         |
| 10                      | 4                      |                 | 5         |           | 3         |           | 4         |           | 2         |
| 11                      | 4                      |                 | 2         |           | 6         |           | 6         |           | 5         |
| 12                      | 4                      |                 | 3         |           | 4         |           | 2         |           | 6         |
| 13                      | 4                      |                 | 1         |           | 2         |           | 5         |           | 4         |

Note: See Figure 3 for Location of Seats

# APPENDIX B

## TIFS AND PRQA TEST DATA

TIFS FLIGHT 333

Date 8-15-74

| SEGMENT | RESPONSE |      |         | VERT (R)   | TRANS (R)  |
|---------|----------|------|---------|------------|------------|
|         | N        | MEAN | STD DEV | (RMS G)    | (RMS G)    |
| 1       | 10       | 1.80 | .632    | 2.5323E-02 | 1.4734E-02 |
| 2       | 10       | 1.90 | .738    | 4.4850E-02 | 1.4541E-02 |
| 3       | 10       | 2.70 | 1.059   | 8.1026E-02 | 1.5058E-02 |
| 4       | 10       | 3.00 | 1.054   | 1.0150E-01 | 1.4356E-02 |
| 5       | 10       | 2.40 | .966    | 6.2135E-02 | 1.3786E-02 |
| 6       | 10       | 4.10 | .876    | 1.4678E-01 | 1.4037E-02 |
| 7       | 10       | 2.80 | 1.229   | 5.4921E-02 | 1.4163E-02 |
| 8       | 10       | 2.30 | .949    | 3.2023E-02 | 1.3816E-02 |
| 9       | 10       | 3.90 | 1.101   | 1.0946E-01 | 1.3856E-02 |
| 10      | 9        | 3.56 | 1.333   | 8.9628E-02 | 2.0402E-02 |

PRQA Vertical Motion,  $a_z$ , RMS Values

| Test Run \ Seg | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    |
|----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 1              | .0163 | .0198 | .0288 | .0316 | .0252 | .0430 |       | .0156 | .0326 | .0264 |
| 2              | .0164 | .0194 | .0285 | .0316 | .0250 | .0429 | .0197 | .0156 |       | .0261 |
| 3              | .0159 | .0195 | .0285 | .0317 | .0250 | .0429 | .0198 | .0154 | .0330 | .0264 |
| 4              | .0163 | .0195 | .0285 | .0316 | .0250 | .0430 | .0199 | .0157 | .0331 | .0264 |
| 5              | .0166 | .0199 |       | .0330 | .0257 | .0425 | .0202 | .0161 | .0327 | .0263 |
| 6              | .0158 | .0192 | .0293 | .0331 | .0258 | .0425 | .0202 | .0145 | .0300 | .0245 |
| 7              | .0143 | .0176 | .0271 | .0307 | .0236 | .0393 | .0191 | .0146 | .0300 | .0249 |
| 8              | .0153 | .0179 | .0277 | .0313 | .0241 | .0405 | .0196 | .0149 | .0308 | .0251 |

Test 1 = Test Run 1 + Test Run 2

Test 2 = Test Run 3 + Test Run 4

Test 3 = Test Run 5 + Test Run 6

Test 4 = Test Run 7 + Test Run 8

PRQA COMFORT RESPONSE MEANS,  $\bar{C}$

| Test Run \ Seg | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    |
|----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 1              | 3.333 | 3.167 | 3.833 | 4.167 | 4.333 | 5.167 | 4.667 | 4.500 | 4.500 | 4.667 |
| 2              | 2.333 | 2.377 | 2.833 | 3.000 | 3.373 | 3.667 | 2.667 | 3.000 | 3.167 | 3.167 |
| 3              | 4.333 | 4.500 | 4.500 | 5.167 | 4.000 | 4.500 | 4.333 | 4.000 | 4.667 | 4.667 |
| 4              | 3.167 | 3.167 | 3.167 | 3.833 | 3.833 | 3.500 | 3.000 | 3.00  | 3.167 | 3.167 |
| 5              | 3.333 | 3.167 | 3.500 | 3.500 | 4.167 | 4.000 | 4.000 | 3.833 | 3.833 | 3.667 |
| 6              | 2.667 | 2.833 | 3.000 | 3.167 | 3.333 | 3.167 | 2.833 | 2.833 | 2.833 | 3.000 |
| 7              | 2.833 | 2.833 | 3.333 | 3.667 | 4.167 | 4.333 | 4.333 | 4.167 | 4.167 | 4.167 |
| 8              | 2.167 | 2.333 | 2.500 | 2.333 | 2.167 | 3.000 | 2.500 | 2.333 | 2.500 | 2.333 |

Test 1 = Test Run 1 + Test Run 2

Test 2 = Test Run 3 + Test Run 4

Test 3 = Test Run 5 + Test Run 6

Test 4 = Test Run 7 + Test Run 8

## APPENDIX C

### DERIVATION OF HYPOTHESES AND $\alpha$ VALUE FOR SLOPE COMPARISONS

Three steps need to be completed in order to arrive at the correct set of hypotheses and the  $\alpha$  value with which to use for comparing the slope values by t-tests. These three steps are: 1) formulation of appropriate hypotheses; 2) derivation of  $\alpha$  value; and 3) derivation of t-statistic and comparison of the chosen  $\alpha$  value with probable true  $1-\alpha$ , the probability of accepting  $H_0$  if true.

Hypothesis formulation was accomplished by examination of the error probability of the desired results, i.e., are the PRQA slopes  $b_{p_i}$ , similar to the TIFS slope  $b_T$ ? If this statement was the null hypothesis, then the t-test would be based on:

$$H_0: b_{p_i} = b_T$$

$$H_1: b_{p_i} \neq b_T$$

Now the errors for this set of hypotheses could be stated as:

Type I: PRQA would not be used, but PRQA and TIFS are similar.

TYPE II: PRQA would be used, but PRQA and TIFS are not similar.

Clearly, TYPE II error is more important because future tests results from the ground-based simulator, which were used to design a flight vehicle, would not represent true passenger comfort in flight. If  $\beta$  is the probability of making a TYPE II error, then it should be minimized. With an inverse relationship existing between  $\alpha$  and  $\beta$ , i.e.,  $\alpha = k \frac{1}{\beta}$ , where  $k = \text{constant}$ ,

we should maximize  $\alpha$ . This is a difficult method to use for statistical purposes. Therefore, if the hypotheses can be rearranged, we can achieve a situation in which we minimize  $\alpha$ .

The original hypotheses could be rewritten as:

$$H_0: |b_{P_i} - b_T| \geq \Delta$$

$$H_1: |b_{P_i} - b_T| < \Delta$$

where  $\Delta$  is some value which is attributable to experimental inaccuracies. That is to say some difference is acceptable.

The choosing of an  $\alpha$  is a two-step process consisting of relating the sample size to the normal distribution and then picking  $\alpha$ . The sample size is related to the independent variable of the normal function by the following equation (4, page 2):

$$\frac{\Delta\sqrt{n}}{S_1} \geq k$$

where

$k$  = Independent variable of the normal function

$S_1$  = the population standard error of estimate for this test.

To find  $S_1$ , we need to remember that:

$$S_{Y|X_i}^2 = \frac{S_1^2}{\sum_{j=1}^n (a_{z1} - \bar{a}_z)^2} \quad (1, \text{page 336})$$

and

$$S_x^2 = \frac{\sum_{j=1}^n (a_{z1} - \bar{a}_z)^2}{N_i - 1} \quad (12, \text{page 70})$$



Thus giving the population standard error of estimate for each PRQA test as:

$$S_i = \sqrt{(S_x^2)(n_i - 1)(S_{y|x_i}^2)}$$

This yields the values of:

| <u>Test</u> | <u>S<sub>i</sub></u> |
|-------------|----------------------|
| 1           | 0.71805              |
| 2           | 0.66073              |
| 3           | 0.45200              |
| 4           | 0.81535              |

Before the actual table of k values is formed, the critical values of k,  $k_{cr}$ , need to be established from the normal function using a table of the normal distribution found in any text on probability such as references 1, 11, and 12. Using common values for  $\alpha$ , the critical k values are:

| <u><math>\alpha</math></u> | <u><math>k_{cr}</math></u> |
|----------------------------|----------------------------|
| .01                        | 2.32                       |
| .02                        | 2.06                       |
| .05                        | 1.65                       |
| .10                        | 1.29                       |

Now the calculated k values are as follows, using  $\Delta$  values corresponding to 1, 2, 3, 4, 5, and 10% of  $b_T$ :

| <u><math>\Delta</math></u> | <u>Test No.</u> |          |          |          |
|----------------------------|-----------------|----------|----------|----------|
|                            | <u>1</u>        | <u>2</u> | <u>3</u> | <u>4</u> |
| .1915                      | 1.100           | 1.263    | 1.797    | 1.024    |
| .3829                      | 2.199           | 2.526    | 3.594    | 2.047    |
| .5744                      | 3.298           | 3.789    | 5.391    | 3.071    |
| .7658                      | 4.397           | 5.052    | 7.188    | 4.094    |
| .9573                      | 5.497           | 6.315    | 8.985    | 5.118    |
| 1.9145                     | 10.993          | 12.630   | 17.969   | 10.235   |

A  $\Delta$ , inherent difference of slopes due to experimental error, of 3%, .5744, is very acceptable for this experiment validation program, so the option is chosen to conduct the t-tests at an  $\alpha$  level of .01. That is, at the  $\Delta$  value of .5744, all k values are greater than k critical for an  $\alpha$  equal to .01. Thus we have our level of significance,  $\alpha$ , set at .01.

The third step is to set up the t statistic and compare our  $\alpha$  level with the probable true state of nature, or the probability of accepting a true  $H_0$ , by use of the OC charts. When comparing estimators for equality, the t statistic is formulated thusly, for small samples:

$$t = \frac{(b_{P_1} - b_T)}{\sqrt{1-r^2}} \sqrt{n-2} \quad (12, \text{page } 247)$$

However, when comparisons are made with a specified alternative, the numerator part in parentheses needs to have a plus or minus  $\Delta$  added to it or in this situation, the numerator would have a  $\pm .5744$  (5, page 3). Thus the t statistic is:

$$t = \frac{(b_{P_1} - b_T \pm .5744)}{\sqrt{1-r^2}} \sqrt{n-2}$$

Now the abscissa for the OC charts is  $d$ , where:

$$d = \frac{|b_{P_1} - b_T|}{S_1 \sqrt{\frac{n-1}{\sum_{j=1}^n (x_j - \bar{x})^2}}} \quad (1, \text{ page 234})$$

for a  $t$ -test using hypotheses of the difference being zero. Thus using the same logic, as in the development of the  $t$  statistic for the previously-developed hypotheses, the numerator should be expanded. Additionally,  $S_1$  can be estimated:

$$S_1^2 = S_{y|x_1}^2 \left( \frac{n}{n-2} \right) \sum_{j=1}^n (x_j - \bar{x})^2$$

where  $\frac{n}{n-2}$  is the small sample factor.

Making the substitutions gives  $d$  as:

$$d = \frac{|\hat{b}_{P_1} - \hat{b}_T \pm .5744|}{S_{y|x_1} \sqrt{\frac{(n)(n-1)}{n-2}}}$$

Whether plus or minus .5744 is chosen in the numerator is determined such that  $d$  is maximized or in this case, the value inside of the absolute value signs is maximized. Now  $d$  can be calculated and used on an OC chart for an  $\alpha = .01$  (1, page 203):

| <u>PRQA Test No.</u> | <u>d</u> | <u>True State</u> |
|----------------------|----------|-------------------|
| 1                    | .333     | .89               |
| 2                    | .014     | .99               |
| 3                    | .075     | .98               |
| 4                    | .035     | .99               |

Thus the true probability,  $1 - \alpha$ , accepting  $H_0$  when it is true, is about 99% except for PRQA Test 1.

## APPENDIX D

### TEST SUBJECT FLIGHT PROFILES AND COMFORT SCALE INTERPRETATION

TEST SUBJECT-01

Profile:

Sex: male

Age: 33

Number of flights: greater than 195 hours

Types of Aircraft: general aviation - 75 hrs, military - 20 hrs,  
commercial - more than 100 hrs

Number of simulator flights: 2 hrs

TIFS flights: yes

Attitude towards flying: Enjoy flying helicopters and general aviation.

Never completely comfortable in large jets although I enjoy flying--never quite overcame anxiety.

7-Point Comfort Scale Interpretation:

Neutral - Interpreted as absence of sensation of discomfort

Ratings below neutral would take some form of active comfort stimulus or pleasantries, i.e., interesting view, good looking stewardess, extremely comfortable seat, etc.

Ratings above neutral vary with severity of motion and/or noise or seat discomfort.

Vertical motions bias very little effect on comfort--lateral motion is more disturbing.

TEST SUBJECT-02

Profile:

Sex: male

Age: 28

Number of flights: 135 flights

Types of Aircraft: general-60 hours, commercial-75 hours,  
military-100 hrs

Number of simulator flights: 0

TIFS flights: No

Attitude towards flying: I prefer flying as a mode of transportation

7-point Comfort Scale Interpretation:

1. Very comfortable--This is what I would design to. Completely unnoticeable.
2. Comfortable - Motion or noise barely perceptible--I could work, sleep, etc. with no trouble.
3. Slightly comfortable - Short period of motion, noise that are disturbing, otherwise comfortable.
4. Neutral - This is impossible to express, not slightly comfortable or slightly uncomfortable.
5. Slightly uncomfortable - Several periods of distracting motions, noise.
6. Uncomfortable - Flight is distracting throughout.
7. Very uncomfortable - Flight is disagreeable to the point that I would not fly again.

TEST SUBJECT-03

Profile:

Sex: male

Age: 28

Number of Flights: 250 hours

Types of Aircraft: general aviation - 10 hours, commercial - 200 hrs.,  
military - 40 hrs.

Number of simulator flights: 10 hrs

TIFS Flights: Yes extensively

Attitude towards flying: I enjoy flying very much, but have  
occasionally (in bad weather) felt apprehension.

7-Point Comfort Scale Interpretation:

1. Very comfortable - Motion only perceptible if at all -- No  
speech interference from noise, temperature, just right.
2. Comfortable - Motion more than just perceptible, but doesn't  
interfere with activity at all.
3. Slightly comfortable - Might not want to drink hot coffee here.
4. Neutral - Aware enough of noise, motion, temperature, etc.,  
that concentration is difficult.
5. Slightly uncomfortable - Begin to concentrate on looking for  
the ground for assurance all is ok.
6. Uncomfortable - Nose against the window, eyes wide open and down.
7. Very uncomfortable - Tighten the seat belt and look for a pillow.



TEST SUBJECT-04

Profile:

Sex: male

Age: 46

Number of flights:

Types of Aircraft: military-1000 hrs, commercial-30 flights  
general aviation-50 hrs

Number of Simulator flights: 50 hrs

TIFS flights: Yes

Attitude towards flying: Like it.

7-Point Comfort Scale Interpretation:

1. Very comfortable - as seated in my den watching television.  
Comfortable chair, temperature just right, no extraneous noise.
2. Comfortable - Slight deviation in one of the above.
3. Slightly comfortable - Noise level higher than normal office,  
or mild turbulence.
4. Neutral - Condition where undesired input (noise, motion, or  
visual) could be tolerated for a long period, without fatigue  
exceeding daily working environment.
5. Slightly uncomfortable - Only occasionally aware of discomfort.
6. Uncomfortable - Almost continuously aware of discomfort.
7. Very uncomfortable - 100% aware of discomfort and would include  
being physically ill.

TEST SUBJECT-07

Profile:

Sex: male

Age: 33

Number of flights: 15 flights

Types of aircraft: commercial

Number of simulator flights: 1

TIFS flights: No

Attitude towards flying: Enjoy flying.

7-Point Comfort Scale Interpretation:

Just sitting there in the airline seat is uncomfortable. Neutral is motion that improves on that. Very few of the motions were uncomfortable but the noise did complicate judgments. Initially the noise was annoying but it was less so after a few minutes.

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TEST SUBJECT-08

Profile:

Sex: male

Age: 42

Number of flights: 265 hours

Types of aircraft: general aviation-15 hrs, commercial-250 hrs.

Number of simulator flights: 50 hrs.

TIFS flights: No

Attitude towards flying: Enjoy it.

7-Point Comfort Scale Interpretation:

1. Very comfortable - Good for indefinite flight. No perceptible noise.
2. Comfortable - Good for indefinite flight. Slightly perceptible noise.
3. Slightly comfortable - Good for indefinite flight. Noticeable noise.
4. Neutral - Good for long (1-1/2 hrs) flight. Very noticeable noise.
5. Slightly uncomfortable - Up to 1/2 hour. Strongly noticeable, unpleasant noise.
6. Uncomfortable - Very short flight, unpleasant noise.
7. Very uncomfortable - Help!

Noise had a definite effect on my measure of comfort since it is too directional to be representative of flight.

TEST SUBJECT -09

Profile:

Sex: male

Age: 23

Number of flights:

Types of aircraft: general aviation-120 hrs, commercial 30-40 hrs,  
military-5-100 hrs

Number of simulator flights: 2-3 hrs.

TIFS flight: Yes

Attitude towards flying: Enjoy it.

7-Point Comfort Scale Interpretation:

1. Very comfortable,- Straight and level flight, comfortable temperature, no sharp changes in motion.
2. Comfortable - Straight and level flight, tolerable temperatures, moderate changes in motion allowable.
3. Slightly comfortable - Straight and level flight, tolerable temperatures, somewhat bumpy, however reading or writing could still be done reasonably well.
4. Neutral - Climbs, turns, large bumps, difficult reading, however still possible.
5. Slightly uncomfortable - Cannot read, cannot sleep because of motion.
6. Uncomfortable - Feeling sick to stomach.
7. Very uncomfortable - Feeling as if ready to throw-up.

TEST SUBJECT-10

Profile:

Sex: female

Age: 36

Number of flights: 60 to 100

Types of aircraft: mostly commercial, some general aviation,  
B-707, 737, 747, YS-11, Cessna, piper

Number of simulator flights: VMS-50 times, RDS-2 days

TIFS flight: Yes

Attitude towards flying: I still love it.

7-Point Comfort Scale Interpretation:

1. Very comfortable - At home, environment quiet, peaceful, relaxed.
2. Comfortable - One or two variables noticeable, i.e., temperature, noise.
3. Slightly comfortable - Activities may be becoming more difficult, motion may be affecting ability to perform selected activities and periodically annoying.
4. Neutral - Neither comfortable nor uncomfortable.
5. Slightly uncomfortable - Motion or vibration along with extreme temperature level making life unpleasant.
6. Uncomfortable - Thrown around, stomach and head reacting to motion or environment and beginning of airsickness.
7. Very uncomfortable - Airsick.

TEST SUBJECT-11

Profile:

Sex: male

Age: 25

Number of flights: 25

Types of Aircraft: General aviation-5 flights, commercial-20 flights,  
military-none

Number of simulator flights: 5 hours

TIFS flight: Yes

Attitude towards flying: Love it.

7-Point Comfort Scale Interpretation:

1. Very comfortable - Sensation very soothing, relaxing, no anxiety.

At peace with surroundings.

2. Comfortable - Relaxing, no anxiety but not absolutely calm.

3. Slightly comfortable - Equidistant between ratings 2 and 4.

4. Neutral - Neither relaxed nor annoyed with the environment.

5. Slightly uncomfortable - Just a little annoyed with the environment.

6. Uncomfortable - Very annoyed, beginning to feel sick.

7. Very uncomfortable - Just get me out of here! Tolerable only in  
an emergency.

TEST SUBJECT-12

Profile:

Sex: male

Age: 25

Number of flights: 40 hours (14 flights).

Types of aircraft: general aviation-none, commercial aviation-40 hours  
military aviation-none

Number of simulator flights: None

TIFS flights: No

Attitude towards flying: I enjoy flying on commercial airlines. The larger the better.

7-Point Comfort Scale Interpretation:

1. Very comfortable - Music, soothing motion, beautiful clouds.
2. Comfortable - No noise, the motion is soothing.
3. Slightly comfortable - The net effect of the system is slightly positive. For example, there is no noise, and the motion is a little soothing.
4. Neutral - Nothing bothers me about the system. Either the motion or sound is unnoticeable, or I have blocked them out.
5. Slightly uncomfortable - Either the noise or the motion bothers me slightly. For example, I rated a ride "somewhat uncomfortable" because the noise bothered me slightly.
6. Uncomfortable - The noise or the motion begins to get irritating.
7. Very uncomfortable - The system begins to cause pain, headaches, backaches, stomachaches, or perhaps nervousness.

TEST SUBJECT-13

Profile:

Sex: male

Age: 28

Number of flights: 35

Types of aircraft: General aviation & helicopters-10 flights,  
commercial-25 flights

Number of simulator flights: None

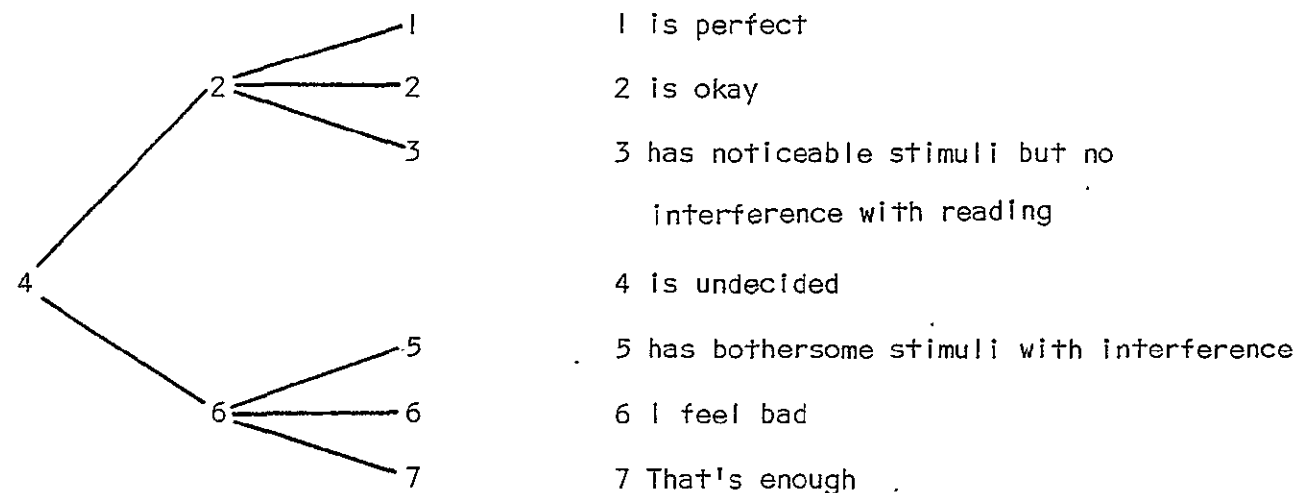
TIFS flight: Yes

Attitude towards flying: It's great!

7-Point Comfort Scale Interpretation:

First I decided if I'm comfortable or uncomfortable.

Second I decided how much I am of one of the above.

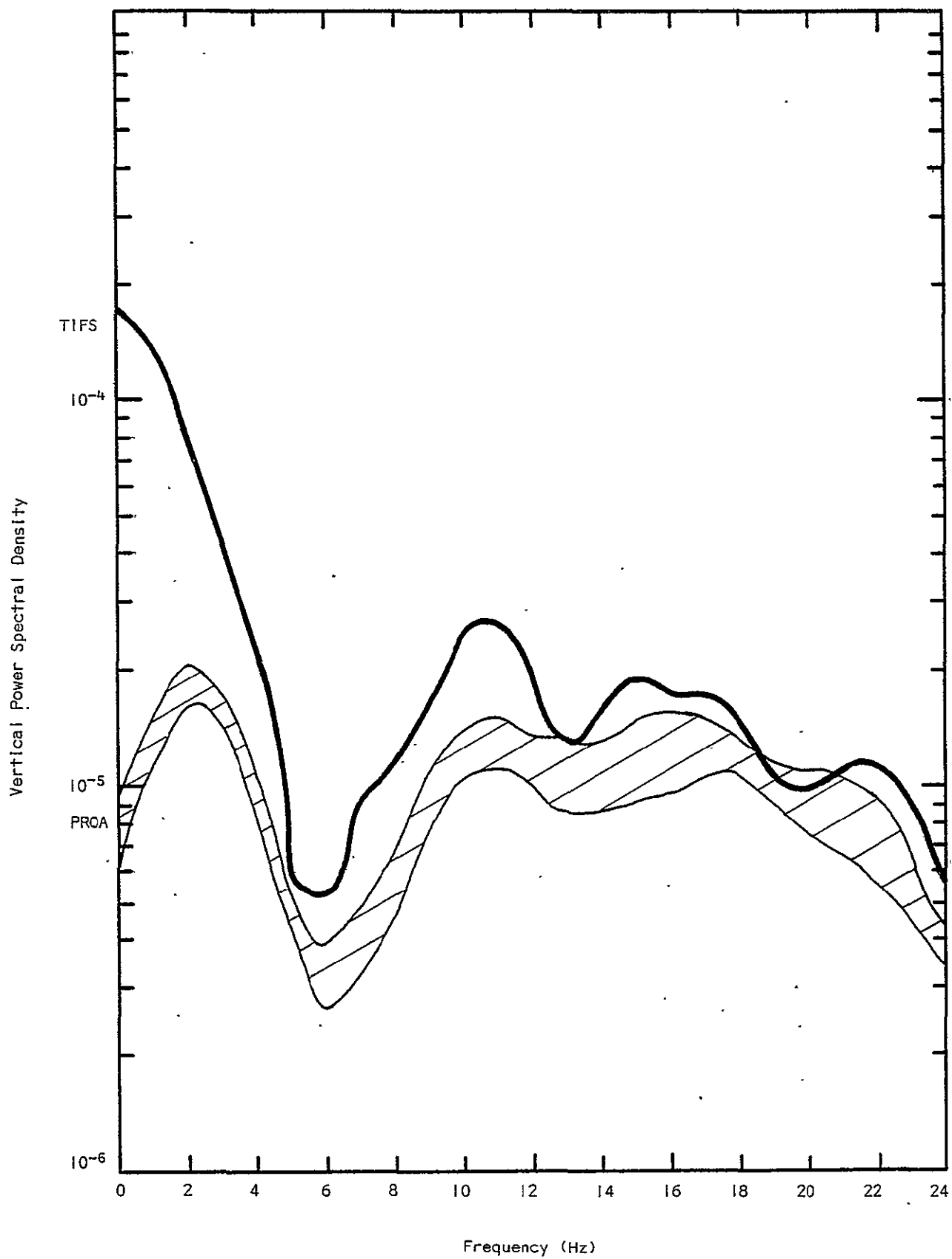




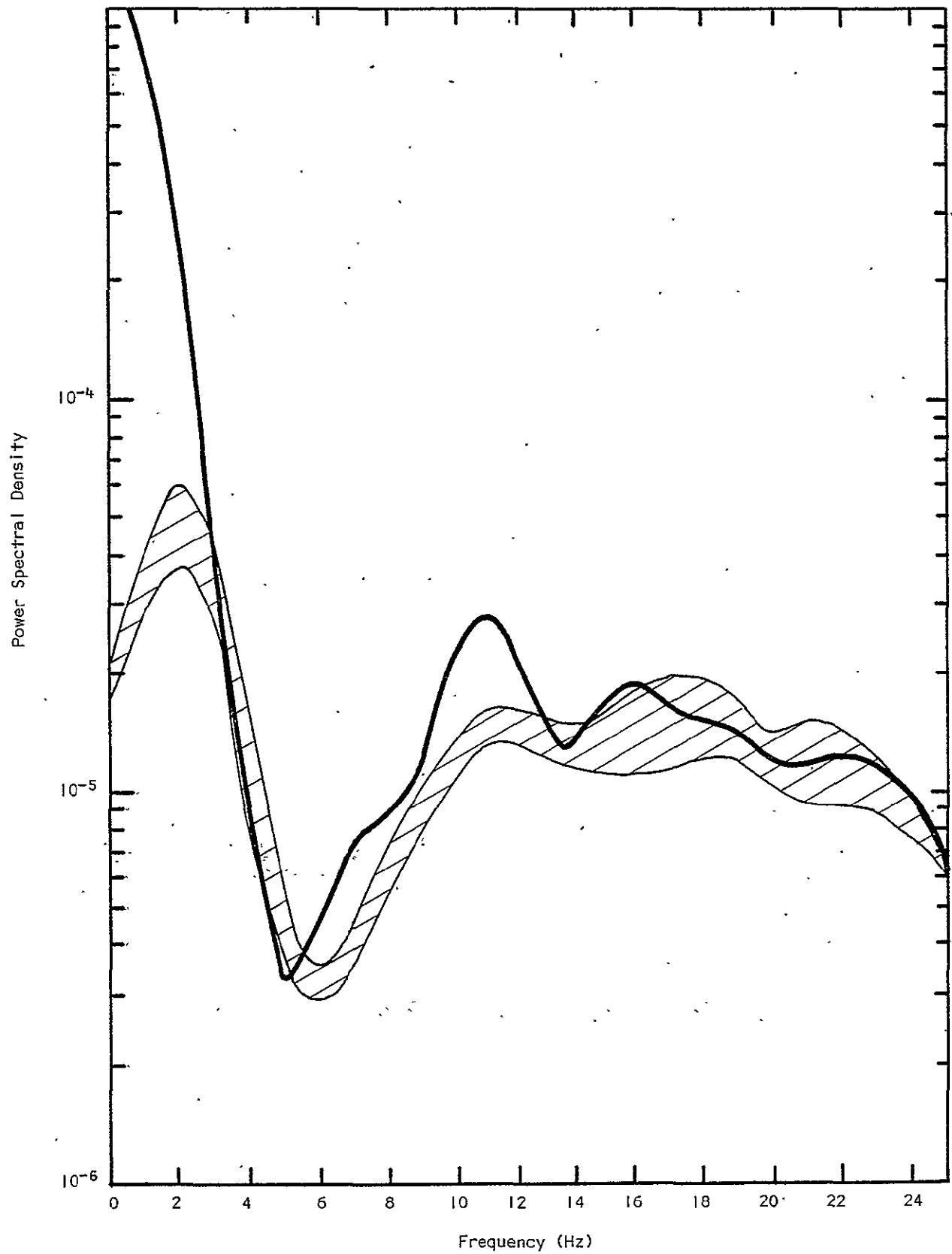
## APPENDIX E

### COMPARISON OF VERTICAL MOTION POWER SPECTRAL DENSITIES BETWEEN PRQA AND TIFS

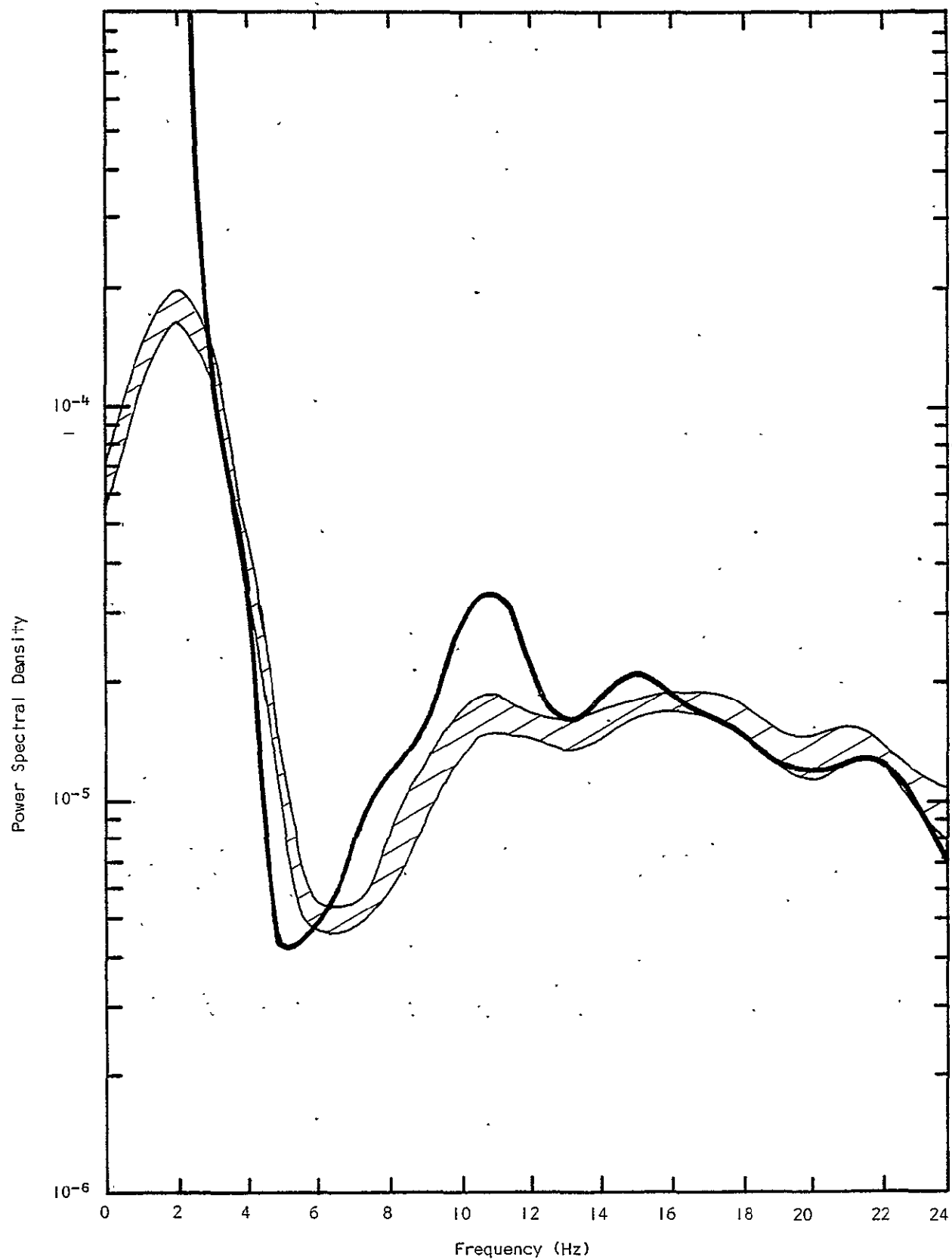
SEGMENT 1 COMPARISON



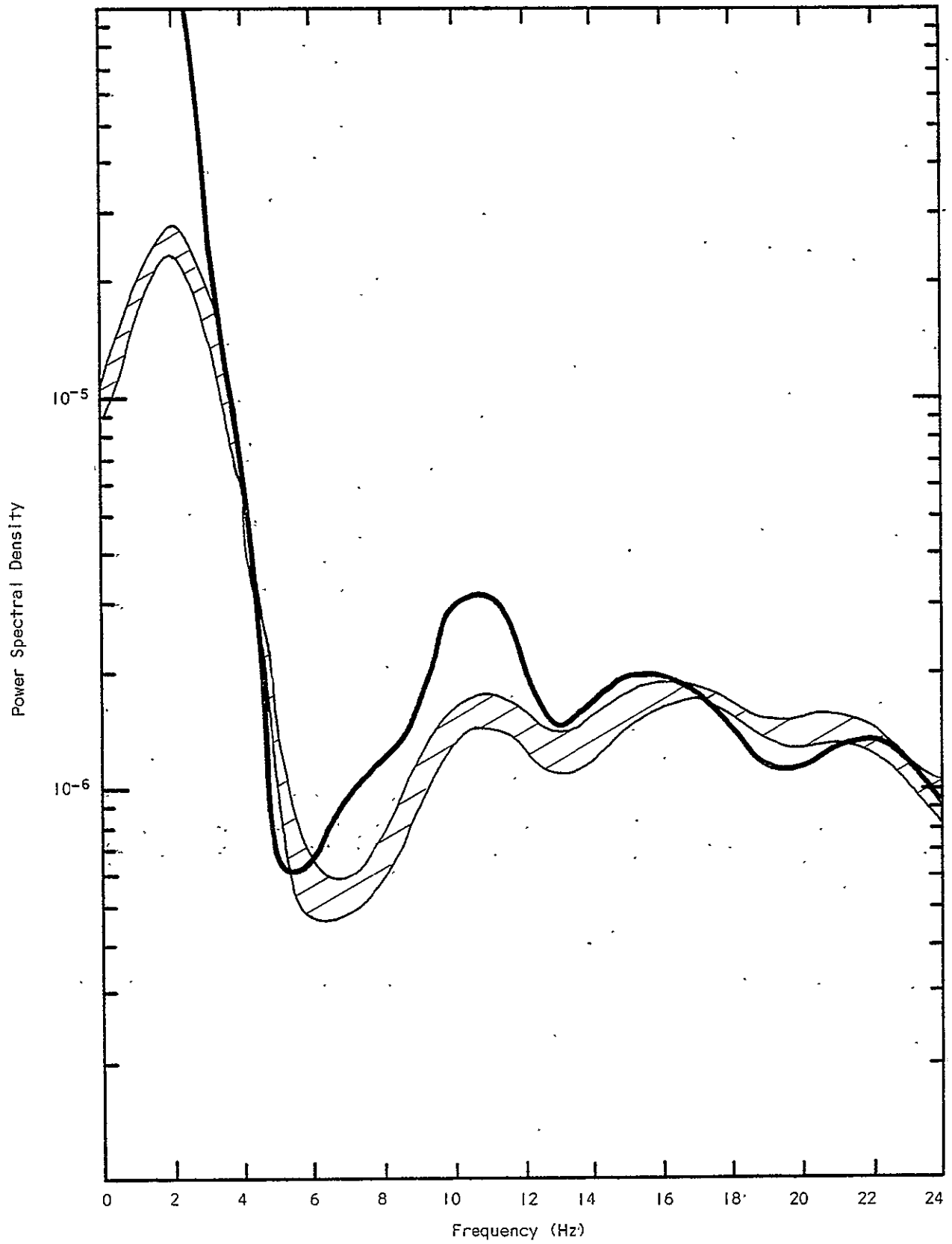
SEGMENT 2 COMPARISON



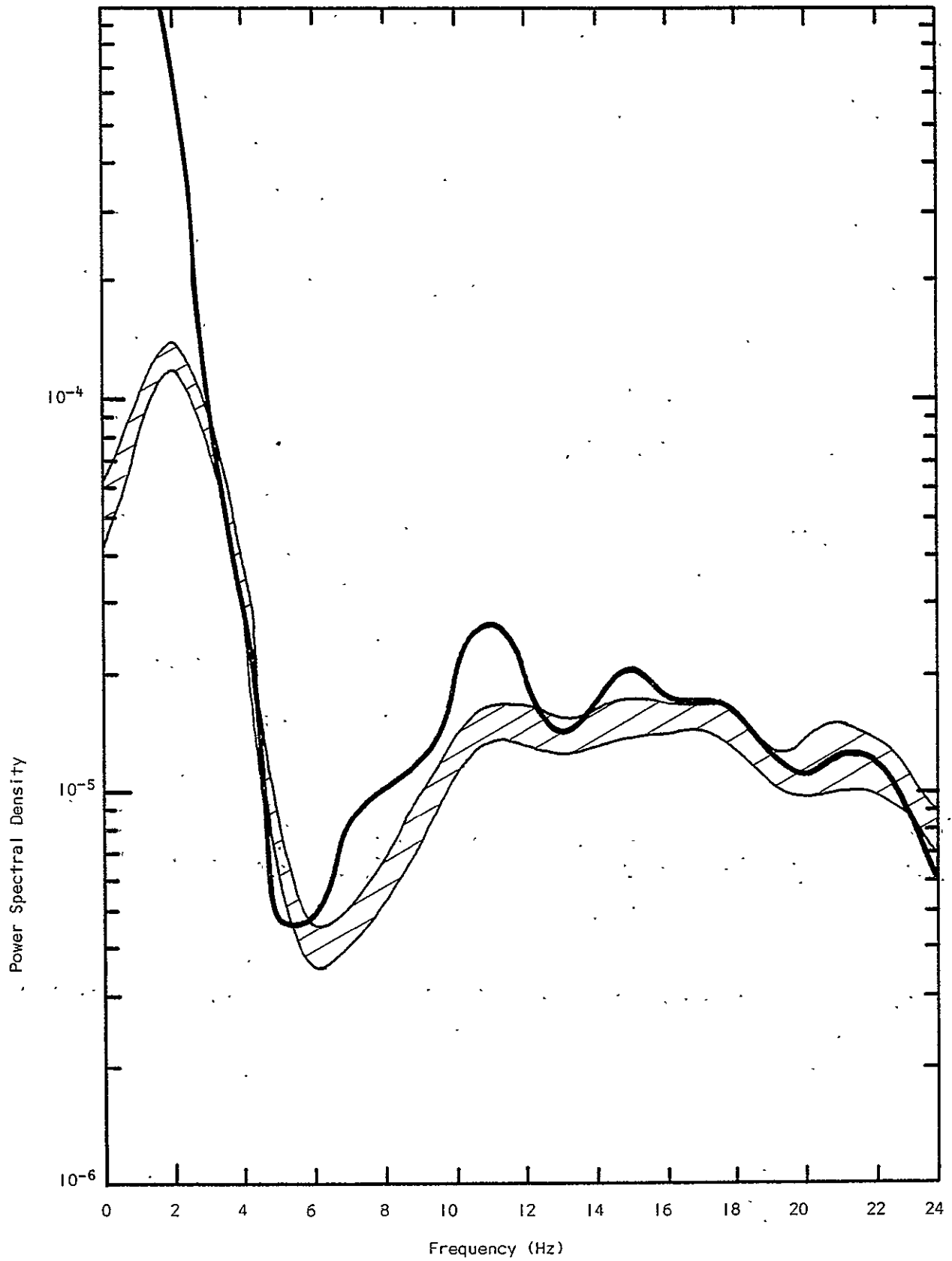
SEGMENT 3 COMPARISON



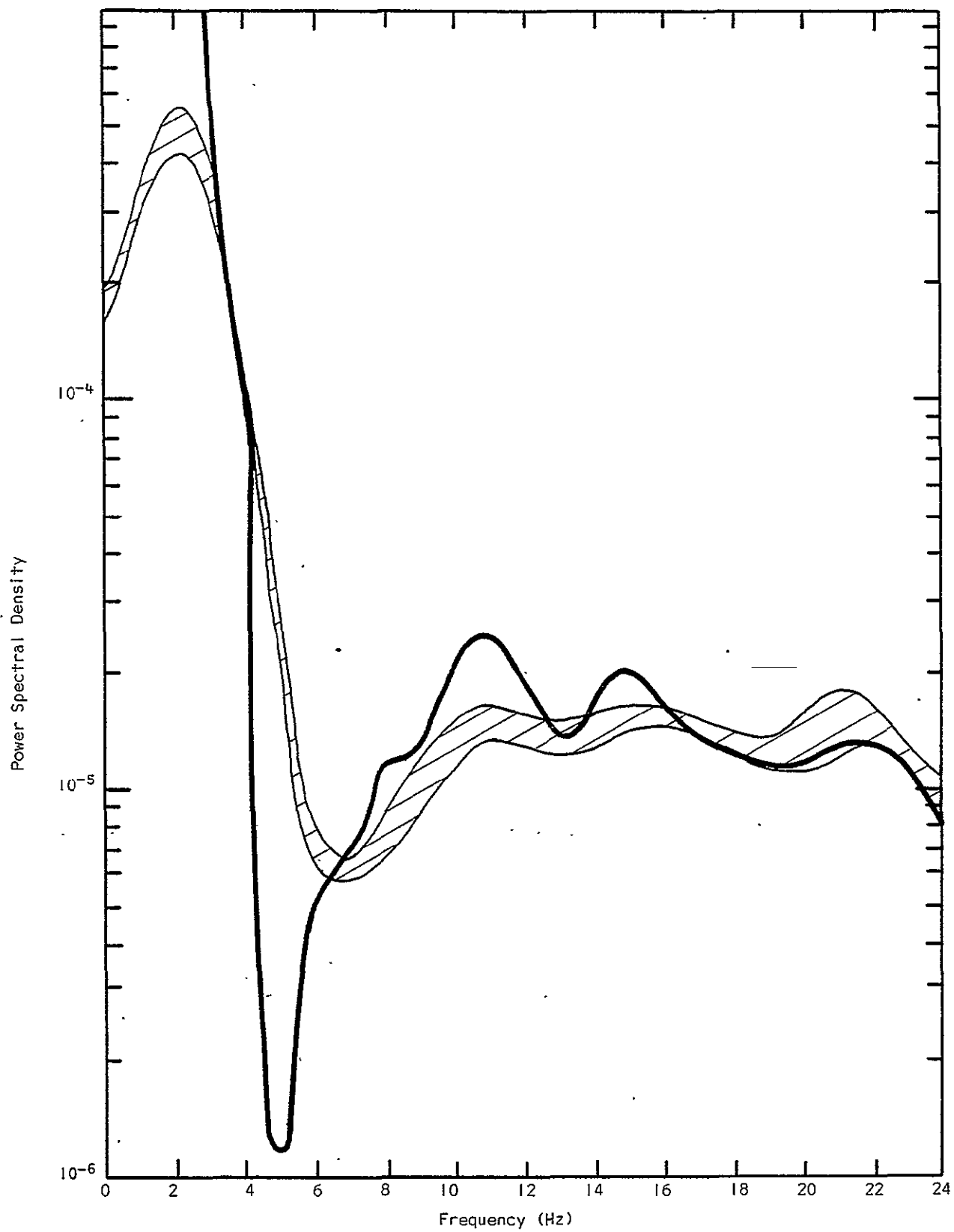
SEGMENT 4 COMPARISON



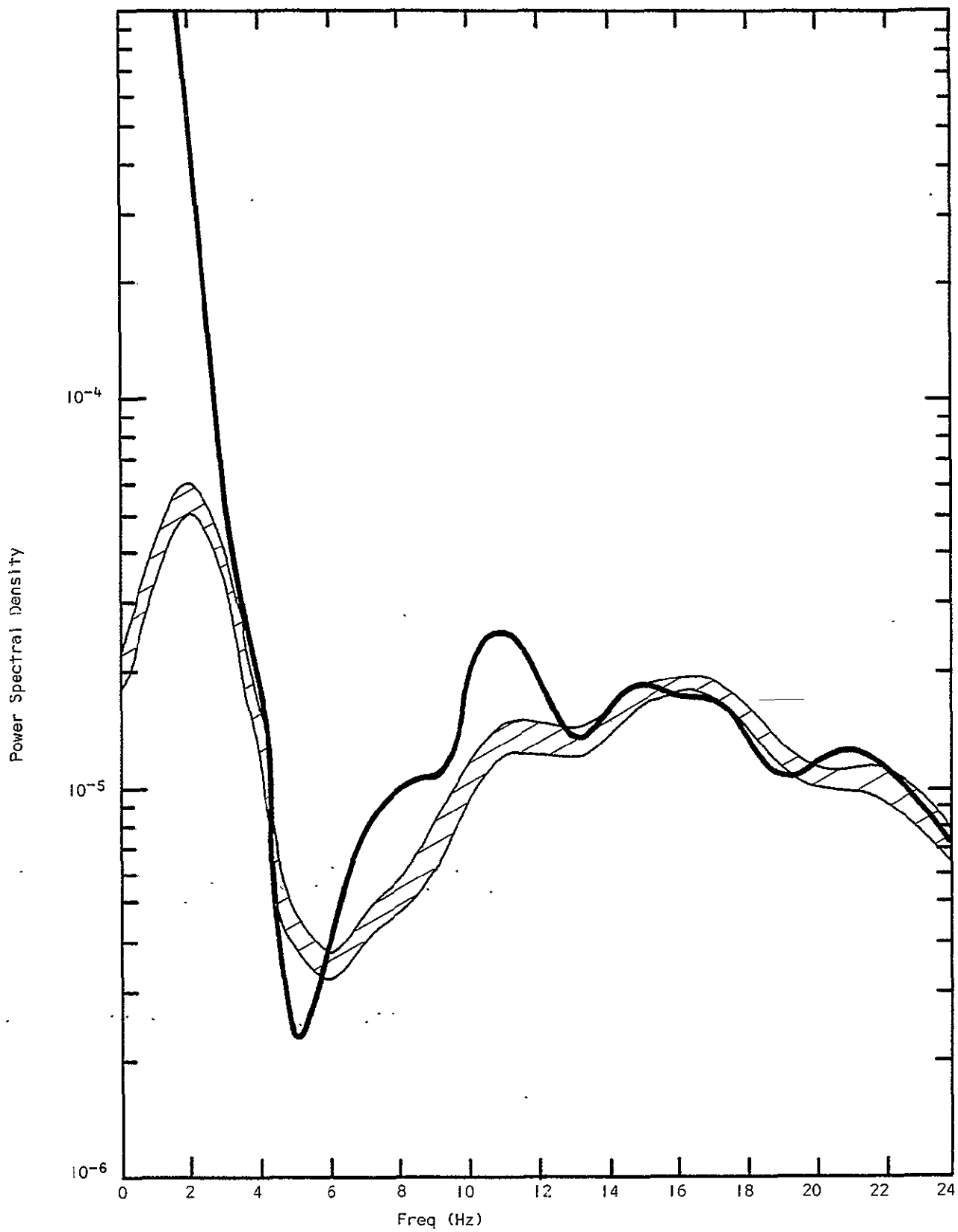
SEGMENT 5 COMPARISON



SEGMENT 6 COMPARISON

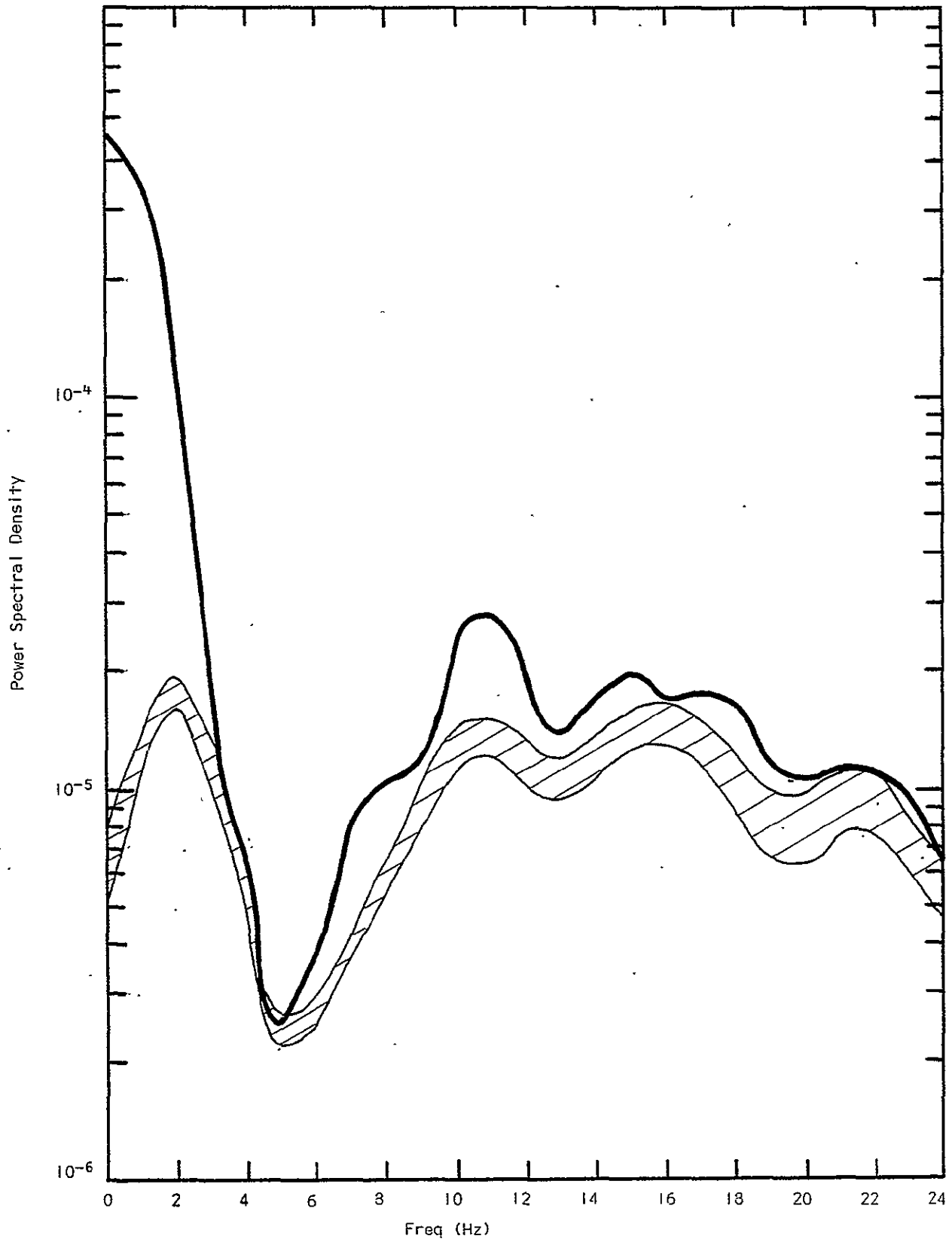


SEGMENT 7 COMPARISON

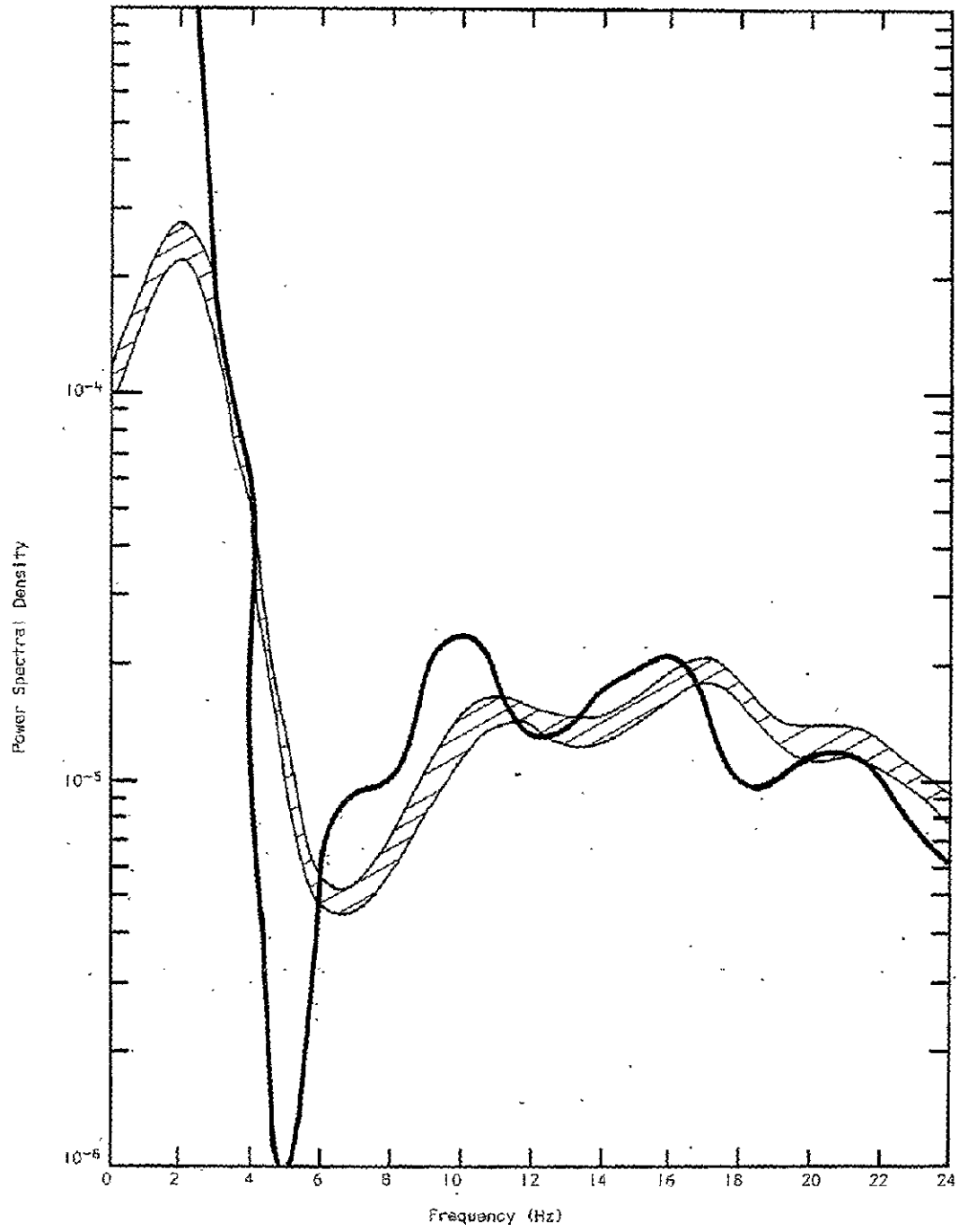




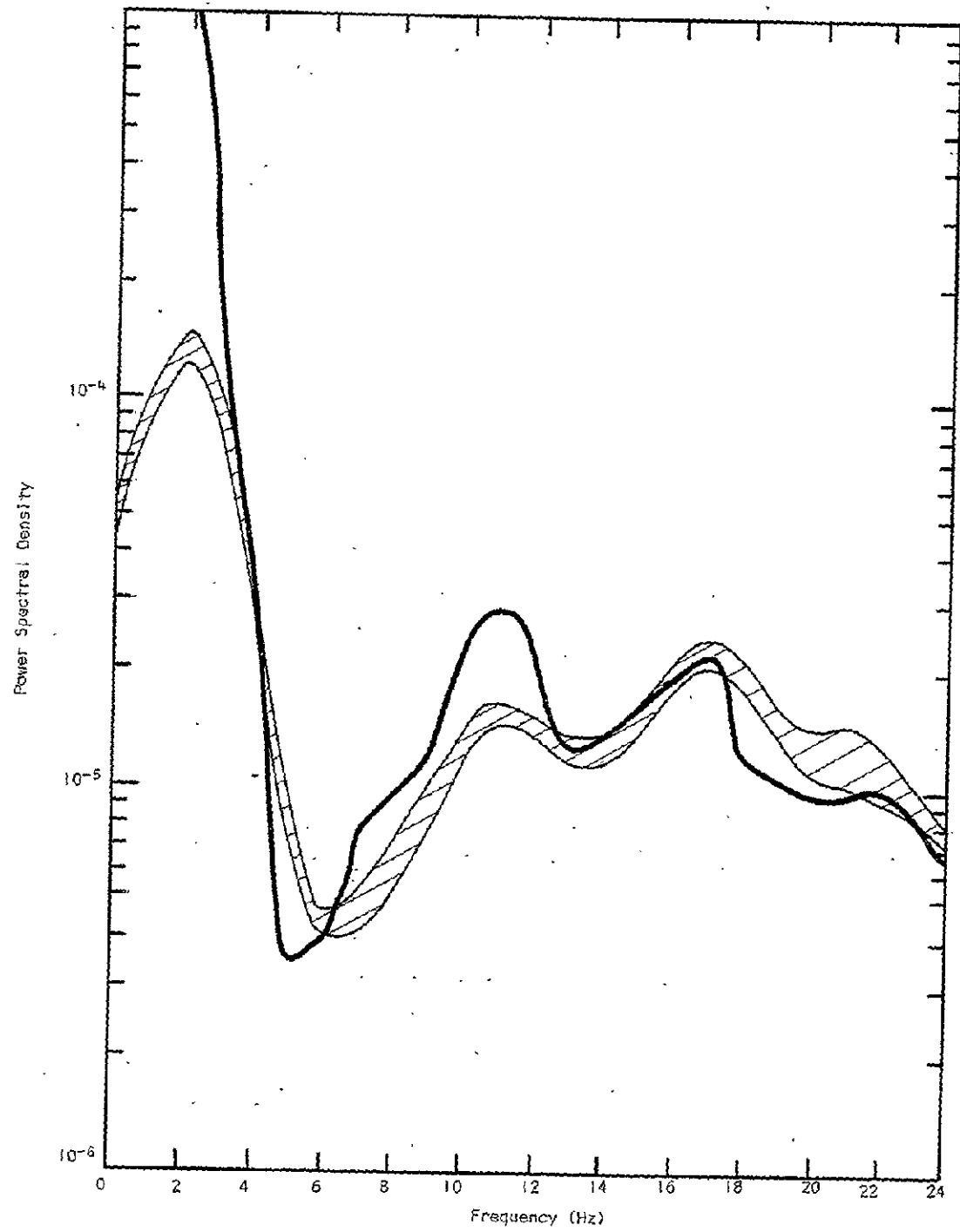
SEGMENT 8 COMPARISON



SEGMENT 9 COMPARISON



SEGMENT 10 COMPARISON



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### **School of Engineering and Applied Science**

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Research is an integral part of the educational program and interests parallel academic specialties. These range from the classical engineering departments of Chemical, Civil, Electrical, and Mechanical to departments of Biomedical Engineering, Engineering Science and Systems, Materials Science, Nuclear Engineering, and Applied Mathematics and Computer Science. In addition to these departments, there are interdepartmental groups in the areas of Automatic Controls and Applied Mechanics. All departments offer the doctorate; the Biomedical and Materials Science Departments grant only graduate degrees.

The School of Engineering and Applied Science is an integral part of the University (approximately 1,400 full-time faculty with a total enrollment of about 14,000 full-time students), which also has professional schools of Architecture, Law, Medicine, Commerce, and Business Administration. In addition, the College of Arts and Sciences houses departments of Mathematics, Physics, Chemistry and others relevant to the engineering research program. This University community provides opportunities for interdisciplinary work in pursuit of the basic goals of education, research, and public service.